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AN EXPERIMENTAL INVESTIGATION OF IGNITION AND FLAME STABILIZATION IN A TURBULENT MIXING ZONE

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OF IGNITION AND FLAME STABILIZATION
IN A TURBULENT MIXING ZONE

Thesis By

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ABSTRACT

The present investigation constituted the first part of an attempt to isolate the essentials of flame stabilization behind a bluff body. It is thought by many that such a flame is initiated and stabilized by heat transfer, the diffusion of active chemical species, and the chemistry of the combustible mixture involved.

The ignition of a fresh combustible mixture by a hot stream of gas provides possibility for detailed study of flame stabilization because of heat transfer.

Results indicate that the method followed herein to produce ignition resulted in the formation of two distinct types of flames. One flame seemed to be affected primarily by temperature, the other was affected by temperature, stream velocity, and fuel-air ratio.

The work was carried on as part of a study of flame stabilization being conducted at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

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I. INTRODUCTION

It has been noted in many investigations that the mechanism of flame stabilization by bluff bodies is associated with the recirculation of hot, partially burned gases behind the body. This zone of recirculating gases acts as an ignition source for the fresh unburned mixture which circulates around the body (Cf. Ref. 1). The ignition source in this case is a source of heat and of active chemical specie. Reactions leading to the formation of combustion waves occur primarily in the mixing zone between the recirculating burned mixture and the combustible mixture passing around the body. To more fully understand the individual factors affecting flame stabilization behind a bluff body, it was decided that a study of the mixing zone between a hot, but unburned gas, and a combustible mixture would prove of value. In this way, the hot spots found in unburned gases would be eliminated. Having eliminated one variable in the flame stabilization process, it is to be hoped that prediction of the effect of the various parameters which are of importance in the ignition process will be easier.

This thesis, then, followed from an attempt to investigate only the effects of heat transfer upon a stream of combustible gas. Combustion in the mixing zone between two parallel streams of gas was considered. One stream was hot air; the other was a cool unburned stream of a combustible mixture. Most of the study was conducted with a mixture of air and acetylene as the combustible gas; a propane-air mixture was also used to a limited extent.

The criterion of combustion in this experiment was the existence of a visible flame. This may seem at first thought to have been a rather crude approach but the initial idea was to obtain the trend of the effects of heat transfer, fuel-air ratio, and relative stream velocities upon ignition. Once this trend is established the investigation could be expanded to include more exact procedures.

The equipment used in carrying out the investigation was designed by Dr. F. H. Wright of the Jet Propulsion Laboratory, California Institute of Technology. It consisted essentially of a means of providing concentric streams of gas, the hot gas being injected as an inner cylindrical stream.

General use was made of the facilities of the Jet Propulsion Laboratory.

II. EQUIPMENT

1. General

A three-dimensional annular duct system was employed. Though not the best system for optical studies, this arrangement has the advantage of reducing edge effects (i.e. boundary layer build-up). Furthermore, by using concentric gas streams with the inner stream as the heat source, a greater surface area was available for ignition than might be obtained with other arrangements.

The inner heated gas was air, the outer cool combustible gas a mixture of air and acetylene.

Since additives to the gas streams might have served as hot spots, none were used to assist in observing flames for fear of destroying the isolation of the problem to one of ignition through thermal and diffusion processes. Before concentrating on the present design, a similar experiment was conducted in a two-dimensional duct using nitrogen as the hot stream and a propane air mixture. This experiment gave the first indication that ignition, solely through thermal processes, might in fact be accomplished. A shift was made to the annular duct to permit the use of larger flow rates. Air rather than an inert gas was used as the heat source to avoid excessive dilution of the combustible mixture. Acetylene was chosen as the fuel because it was believed to be easier to ignite than propane.

2. The Heat Exchanger

The system employed to obtain the hot inner gas stream proved

very reliable and provided good control over the temperature of this stream. A line sketch of the system is given in Figure 1.

Hot air was obtained by passing air through a heated coil. The heat source for the coil was a turbojet can (Fig. 1). All air used in the system was supplied by a Fuller Compressor. Pressure control in the supply system was excellent, never varying by more than 1/4 psi from 70 psi.

No flow aligners were necessary in the settling chamber of the heat exchanger. The turbojet can ignited without difficulty as long as the spark source was clean and gave a hot spark. The fuel used in the turbojet can was Union Oil Company #2 paint thinner. This material most closely approached pentane in composition. Fuel was supplied at 100 psi through 1/4 inch copper tubing. The turbojet can was held in place by the various connections to the can and by wedging of the can spacers between the walls of the heat exchanger tube.

The coil of the heat exchanger was made from 10 feet of 1/2 inch stainless steel tubing with 0.065 inch wall thickness. This tube was made into a coil one foot long and 6½ inches in diameter. The tubing was wrapped 1/4 inch thick with asbestos tape. When in place, the coil fitted tightly into a ceramic liner. Insulation between the coil and outside wall consisted of a 1/2 inch thick alundum tube and a 1/2 inch asbestos liner (Fig. 1). After connection, the coil was further held in place by external piping. Coil life averaged about 12 hours and this was considered quite satisfactory.

Air was supplied to the coil through a 1/4 inch copper tube. This air was passed through a regulating valve and delivered at 20, 30,

or 40 psi depending upon the velocity desired in the inner duct. This air was obtained from a tap in the main supply line.

The coil exit fed into a 3/4 inch steel tube which delivered the hot air to the duct. A thermocouple was installed in this 3/4 inch tube immediately below the duct (Figs. 2 and 3). This thermocouple was used to monitor the temperature of the inner jet. Cooling of the heat exchanger exterior was accomplished through water sprinklers arranged at three inch intervals along the top of the tube between the heat exchanger outlet and the blow out patch.

3. The Combustible Mixture System.

The air portion of the system was supplied from the main air supply (Fig. 1). This air was fed through a Fischer and Porter rotameter where volume flow was measured. Flow rates in this line were varied by means of a check valve immediately downstream of the rotameter. Pressure was maintained at 68½ ± 1/2 psi at all times. The temperature of the air was obtained from a mercury thermometer installed in a thin walled well at the top of the rotameter. The well was filled with Meriam Oil.

The acetylene flow was likewise measured through a rotameter. Operating pressure in this line varied from 19 to 86 psi and was recorded from a 100 psi Victor gauge. The same arrangement for noting fuel temperature was made as with the air rotameter.

The fuel was supplied to the rotameter from three 315 cubic feet capacity bottles. These bottles were manifolded together to provide relatively high flow rates without depressing the gas temperature

to the point of liquefaction. The maximum flow rate used was 1,780 cc/sec; the minimum temperature recorded was 11°C.

From the rotameter the fuel was carried through 1/4 inch copper tubing to a junction with the air line (Figs. 1 and 3). The major portion of the mixing of the fuel and air took place at this junction and between the junction and the annular duct.

4. The Annular Duct.

A detailed sketch of this duct is presented in Figure 2. The hot air passed directly up through the center of the duct. A thermocouple junction, previously mentioned, extended into this flow but its size was not such as to disturb the flow. Tests were performed (see Procedure) which showed the flow in both inner and outer ducts to be sufficiently symmetrical for the purpose of this investigation. A thermocouple junction, not shown, was also installed at the wall through this same break in the hot air supply line. It was necessary that the wall temperature be known to correct the observed gas temperature for radiation effects (Appendix I).

The fuel-air mixture was supplied to a 1/2 inch outside diameter injection ring (Figs. 2 and 4). A top view of the annular duct, (Fig. 4) and an enlarged view of the duct (Fig. 5) show this ring clearly. Twenty-two equally spaced holes of 0.137 cm diameter were drilled through the outer periphery of this ring for injection of the fuel-air mixture into the annular duct chamber. By injecting the fuel-air mixture in this manner, a better mixed, more evenly distributed flow was attained. The distribution was further improved by a pressure grid (Figs. 2, 4 and 5). The pressure grid consisted of a steel

ring, also drilled with 0.137 cm diameter holes. Eight equally spaced holes were drilled in a vertical row and 80 rows of holes spaced equally around the ring.

As a final assistance in attaining uniform flow, six guide vanes of sheet metal were installed (Figs. 4 and 5). These vanes butted up against the inside edge of the resistance grid and extended from the floor to the ceiling of the main chamber. The vanes were 4.76 cm long. Details of the inner duct are given in Figures 2 and 6 with a photograph of this component presented in Figure 7.

5. Flame Lift Distance Measuring Device.

The most important parameter measured in this experiment was the distance that the flame bases were lifted above the inner duct exit. A satisfactory, simple, and readily available device to measure these distances was a sliding carpenter's level on a steel rule. A more exact device would not have permitted one to measure flame lift distance with any greater accuracy.

A portion of the lengthwise edge of the rule was imbedded in an aluminum block with the level free to travel the length of the rule. The block and rule were then clamped to the top plate of the annular duct with the rule extending vertically from the top of the plate. The block and rule were clamped behind the flame zone from the observer. The bottom edge of the level was then used as a line with which to cut the base of the lifted flame. This line was raised and lowered to correspond to the height of the flame being observed and readings taken from the rule. The flat underside of the level

served as an aid in insuring a horizontal line of sight between the observer's eye and the measuring device.

6. The Test Cell.

The test cell consisted of a concrete room 24' x 33' and 12' high with one wall completely open to the atmosphere. No darkening of the room was attempted because the annular duct exhausted into the room and any covering of the open wall would have permitted a dangerous quantity of combustible mixture to build up in the room.

Various forms of light shielding in the vicinity of the duct were tried but proved only moderately successful. The flame being observed was either clearly observed at all times or required a completely darkened room. Some test runs were therefore of necessity run at night.

Adjustments to air flow for both the inner and outer ducts were made at stations within the test cell. Acetylene flow and temperature adjustments were made from a protected control room.

III. PROCEDURE

1. The Object of the Experiment

The primary object of the experiment was to obtain ignition of a combustible unburned mixture through thermal processes only. Having obtained ignition, the next objective was to study the effect of varying temperature, fuel-air ratio, and relative stream velocities upon the flame.

Before proceeding, however, it was first necessary to establish the characteristics of the duct.

2. Cold Velocity Survey.

This survey was made to check the physical design or the flow symmetry. The flow aligning vanes, for example, were installed after a survey of this nature indicated that a slight swirl existed in the flow in the outer annulus.

The cold velocity survey was made with a total head tube the thickness of which in the direction of the survey was 0.64 mm on the outside and 0.28 mm on the inside. The outside width of the tube was 2.84 mm. The total head tube inlet was positioned 0.75 mm above the inner duct outlet. The inner duct edge served as a reference point for each reading, the positioning of the probe over this edge being determinable to 0.3 mm.

The total head tube was connected to a Meriam filled micromanometer. The manometer was vented to the atmosphere. A static

pressure survey showed negligible difference between atmospheric pressure and the static pressures in the concentric gas streams. All pressure surveys, therefore, were made with a total head tube with the manometer vented to the atmosphere. Since the region of importance was that in the vicinity of the inner duct, the velocity survey was not carried to the wall of the outer duct.

Figures 8, 9, and 10 present the results of this survey. It is to be pointed out that where reference is made in these figures to upstream pressures in the outer and inner ducts, the pressures are those at the pressure gauge adjacent to the air rotameter and at the pressure gauge adjacent to the hot air pressure regulator, respectively (Fig. 1).

Figure 8 serves primarily as a check on the flow contour produced by the outer duct. The flow, as may be seen in Figure 8, was flat and reasonably symmetrical. Cold air only was admitted to the outer duct.

Figure 9 presents the results of a survey similar to that presented in Figure 8 except that cold air was being passed through the inner duct. An increase in the velocity in the outer duct was noted as was a drop in velocity near the inner duct edge due to wall effects. This last effect disappeared when hot air was admitted to the inner duct.

The velocity profile of both ducts was again sufficiently flat and symmetrical for the purposes of this investigation. There appeared to be a horizontal displacement of the two curves between

the two probes but it was felt that this effect was due to the limitations in determining the reference point for each probe.

Because the symmetry of the velocity profiles was satisfactory, subsequent surveys of velocity and temperature were considered as having been given in full by traversing one diameter only.

Figure 10 is presented to show the mean cold velocity profile. Variations from this profile in the actual surveys did not exceed $\pm$ 2.5%.

3. Velocity Distribution Running Hot.

This survey must be considered in conjunction with the temperature distribution (see Page 12) since the true value of each depends upon the other. The following results, therefore, were arrived at by a series of approximations. The gas density was corrected for temperature from a temperature survey of the flow field. The resulting velocity, however, affected the temperature correction (Appendix I). With a new temperature, a new velocity resulted, etc.

The hot surveys were conducted in the same manner as the cold velocity surveys were conducted except that only one diameter was traversed. Furthermore, the hot air in the inner duct was admitted at three different operating velocities instead of the single velocity used in the cold survey. These conditions were controlled with the hot air supply system pressure regulator valve (Fig. 1) 20, 30 and 40 psi were the settings used.

It should be mentioned here that the total head probe used, see page 7, was of such dimensions as to permit manometer readings to stabilize without excessive delay, yet did not appreciably disturb the

flow conditions. Manometer readings were reproducible to ± .2 mm, or ± 15 cm/sec in velocity, for velocities in the region of 3500-5750 cm/sec. For velocities in excess of 6000 cm/sec, reproducibility was ± 1 mm, or ± 58 cm/sec (Fig. 11).

The symmetry of the velocity profiles was retained when the duct was running hot. The results of the survey are presented in Figure 11. It is interesting to note that the wall effect noted previously (Figs. 9 and 10) disappeared. Note also that there was no change in the velocity in the outer annulus between running hot or cold air through the inner duct. Furthermore, the mass flow in the inner duct, through the operating range, had no effect upon the velocity in the outer duct. No velocity survey was made with acetylene flowing in the outer duct. The amount of the acetylene used, however, was not sufficient to appreciably change the mass flow of the fuel-air mixture from that of air alone. The velocities in the outer duct as given in Fig. 11, therefore, may be considered to be the velocity of the combustible mixture.

4. Temperature Distribution with Hot Air in the Inner Duct.

A temperature survey was made with hot air admitted at various flow rates to the inner duct and unheated air, only, admitted to the outside duct.

This survey served a dual purpose. First, it was made to study the temperature distribution at various inner duct flow rates; Second, it was desired to correlate the temperature recorded immediately before the hot gas entered the annular duct (Fig. 2) with the

temperature of the gas at the duct exit. The distance between these locations was 7.8 cm. Henceforth, the temperature of the hot gas immediately before entering the annular duct will be referred to as the "heat exchanger temperature". The heat exchanger temperature was used as the controlling temperature in subsequent data.

The survey was made with a wedged shaped chromel-alumel thermocouple 0.64 mm thick at the tip and 1.28 mm thick at the top of the wedge. The width was 1.28 mm. The thermocouple was made wedged shaped to give good lateral temperature sensitivity. The probe was located 0.75 mm above the edge of the inner duct and the duct edge served as reference point for lateral position. The resulting profiles presented in Figure 12 are thus made at the same vertical location as the velocity profiles of Figures 8 through 11.

Thermocouple readings were corrected only for radiation following the procedures outlined in Appendix I for the calculation of the true temperature of a gas. Since the location of the probe thermocouple was such that only 1% of its surface "saw" the hot radiating surface within the inner duct, the form factor F was taken as 1. (0.99 would have been an exact value for F.) T_o equalled 300°K and $\varepsilon = 0.87$.

The correction method set forth in Appendix I was based on a spherical thermocouple. Since no information was available for techniques to use for other than spherical or cylindrical shapes, it was decided to lump the correction for the wedge shape into a reduced diameter for Re calculations. Reducing the diameter had the end effect of reducing the correction to be applied to the observed temperature.

This last may reasonably be expected since a wedge is a more efficient heat radiating surface than a sphere. The diameter used in this case was 0.64 mm.

A complete survey was made for flow at 20 psi in the hot air supply line. Air in the outer duct flowed at the maximum rate available, or 31,000 cc/sec. Heat exchanger temperature was held at 1115°K ± 8°. The heat exchanger thermocouple junction was a sphere of 1.68 mm diameter and corrections to observed temperatures in this case followed directly those outlined in Appendix I.

The temperature profiles for 30 and 40 psi in the inner duct supply line were obtained by spot checking the temperatures at the center of the duct and 2.0 mm outside each edge of the inner duct. Curves were then drawn following the basic shape of the curve obtained from the complete survey (Fig. 12).

It is observed in Figure 12 that there was a drop in maximum temperature with increasing velocity in the center duct and that exit temperature exceeded inlet temperature. This is a factual impossibility, of course, but may be explained when all causes are considered.

The error may be attributed to two causes:

First, the emissivity of the particular thermocouple used in the probe though taken as 0.87 or fully oxidized, was probably somewhat less than 0.87 for the 20 psi case and approached 0.87 more closely in the later surveys at 30 and 40 psi. This inaccuracy was introduced through the thermocouple having been shaped only a short time before the surveys were made and thus, complete oxidation of the surface had not yet occurred. The emissivity effect as outlined above

would account for part or all of the discrepancies noted in Figure 12. Since the mean temperature at the duct exit equalled 1150°K and the temperature of the heat exchanger equalled 1105°K, an ϵ of 0.835 for the probe thermocouple would have brought the two temperatures into agreement. The American Journal of Physics (Ref. 2) states that 100 hours at temperature is required for complete oxidation. A private communication from M. Gilbert of the Jet Propulsion Laboratory states that 10 hours at temperature would almost completely oxidize a thermocouple junction. The thermocouple used in this survey was set in the heated air for only one-half hour before any readings were taken. An emissivity of 0.835, therefore, would have been more reasonable than one of 0.87.

The second possible cause for the above discrepancies was the choice of 0.64 mm as the reduced diameter of the probe thermocouple junction. This diameter was probably too large. A smaller diameter would have brought the heat exchanger and duct exit temperatures more nearly together.

Considering the above points, it was felt that there was little drop in temperature from the heat exchanger thermocouple to the probe thermocouple. It was further felt that for a given potential in the heat exchanger thermocouple, the true temperature at the outlet of the inner duct was the same for all velocities in the inner duct. The true temperature for a given potential in the thermocouple varied by only 3°C for each 10 psi variation in the inner duct air supply.

All subsequent references in this thesis to inner stream temperature will presume that heat exchanger temperature corresponded

to the exit temperature.

5. The Final Data.

The final experiment concerned the effect upon combustion when four parameters were varied. These four parameters were: (1) T_i, the temperature of the inner gas stream; (2) V_i, velocity of gas stream in the inner duct; (3) V_o, velocity in outer annulus; (4) F/A, the fuel-air ratio.

The effect of the first of the above parameters was obtained directly by varying heat exchanger temperature.

V_i was varied by varying the upstream pressure in the hot air supply line (Fig. 1). Figure 11 was used to obtain the V_i associated with each pressure in the inner stream supply. For values of T_i other than 1115°K, the data of Figure 11 were readily corrected.

V_o was varied by varying the flow rate through the air rotameter (Fig. 1). Knowing the velocity V_o for a given flow rate (Fig. 11) a direct ratio was involved between flow rates and velocities. One might also, of course, calculate each velocity individually, since the outer duct exit area was known and the flow rate is given by the rotameter in cc/sec. This was done to check the results of the velocity survey presented in Figure 11 and the velocities were found to coincide within 0.5%. In the actual determination of V_o the flow rate used was that of the air rotameter plus a mean value of the flow rate obtained from the acetylene rotameter. The volume flow through the acetylene rotameter was only 4.5 to 5.0% of that through the air rotameter. It is to be noted here that the rotameters do not read directly

in cc/sec. Rotameter readings were obtained in mm of scale which reading was then transferred into volume flow. To accomplish the transformation it was necessary that the temperature of the gas flowing through the rotameter and the pressure against which the rotameter was operating be known. For complete details on the method involved in obtaining volume flow from a rotameter see Ref. 3.

To obtain varying fuel-air ratios, the acetylene flow through its rotameter was varied. Knowing the volume flow rates of fuel and air as given by their respective rotameters, their mass flow rates are obtained by introducing their respective densities. Thus, using the perfect gas law:

$$F/A = \frac{Q \text{ acetylene}}{Q \text{ air}} \quad \frac{\rho \text{ acetylene}}{\rho \quad \text{air}}$$

$$= ..907 \frac{Q\ p/T}{Q\ p/T} \quad \begin{matrix} \text{acetylene} \\ \text{air} \end{matrix}$$

IV. RESULTS AND DISCUSSION

1. Primary Results.

An ignition source is generally defined as a source of heat and a producer of atoms and free radicals which act as chain carriers in a chemical reaction. An electric spark for example, would satisfy this definition. The flow of heat and chain carriers from the ignition source initiate chemical reactions in adjacent layers of combustible mixtures and ignition is said to have occurred. The adjacent layer then in turn becomes an ignition source. In this way a zone of burning propagates (Cf. Ref. 4).

In thermal ignition, if such exists, an ignition source is still a source of heat but no chain carriers exist. Since in the experiment performed there were no hot spots in the heated air, the general concept of an ignition source as one which would, among other things, produce chain carriers, was not duplicated. It was instead shown in this experiment that a combustible mixture may be ignited through heat transfer only. This was an important result of the investigation. To quote from Jost (Cf. Ref. 5) "The cases of definitely established thermal explosions are relatively rare." Since the investigation was primarily a visual process, it cannot unequivocally be stated that pure thermal explosion was initiated but it would seem that very close approximation thereto was attained.

An important result of this experiment, therefore, was the ignition of a cool combustible mixture with a hot gas stream. Numerous

experiments have been conducted wherein both gases were preheated and then mixed to determine ignition temperatures (Ref. 4). In this experiment, however, ignition was attained without preheating the fuel-air mixture. This process more nearly approached conditions behind a flame holder. With reference to flame holders, it must be mentioned again that this investigation was one in which an attempt was being made to isolate the thermal effects in the overall ignition process behind a bluff body. In actual flame holding, there is an adjacent flame which strongly affects the process of ignition. In this experiment, however, there was no hot body or flame near the initial ignition zone. Both inner and outer duct exits were relatively cool and all catalytic influences were thereby eliminated. That is, the surfaces in question were sufficiently cool so as not to introduce reaction chains.

2. General Description of an Acetylene Flame.

Two types of flames were noted. That first appearing and closest to the duct exit was called the initial flame; that which appeared upon subsequent fuel enrichening was called a propagating flame. Figure 13 presents a sketch illustrating five basic stages through which the flames proceeded as fuel-air ratio was progressively increased.

The initial flame was clearly distinguishable only in a darkened room whereas the propagating flame was identifiable at all times. Both flames were light blue in color, becoming more intense with increasing fuel-air ratio in the outer duct. The bases of both flames were well defined, increasing in sharpness with richer mixtures.

Turbulence in the flames in most cases was such that the lift distances measured were reproducible to 0.33 cm for the propagating flame and to 0.2 cm in the case of the initial flame. Fluctuations of the flame base were not appreciably affected by variations in the flow rate in the outer duct but were strongly influenced by inner duct flow rates. The fluctuation of the flame base was so great when velocities in excess of 68 M/sec were used in the inner duct that any measurement of lift distance was precluded.

The appearance of the flames with increasing fuel-air ratios are well defined in Figure 13. (Photographs of two stages are presented in Fig. 14.) It is to be noted in Figure 13 that the flame did not at any time attach itself to the burner rim. Note furthermore, that an inner unignited cone existed in the initial flame. On first appearing (i.e. ignition with minimum fuel-air ratio) the initial flame measured in the neighborhood of 3 cm from base to tip. With higher fuel-air ratio the initial flame lengthened to about 8 cm at which time the propagating flame appeared. Further enrichening then had no noticeable effect upon the initial flame lift distance, though the flame itself continued to become more intense. On the other hand, once the propagating flame appeared, it continually moved closer to the duct as well as becoming more intense with increased fuel-air ratio. As the propagating flame approached the duct exit it became broader and shorter. In the final stage its base almost coincided with that of the initial flame. Further enrichening of the outer duct flow then caused a flashback. It was interesting to note in these final stages that though the propagating flame was very turbulent, its mean base height

was most sharply defined and very nearly stationary. At such times the height of the base above the inner duct exit was measurable to 0.2 cm.

3. <u>The Effects of Varying Parameters upon the Flames</u>.

Since the investigation was to be coupled with flame holder studies, it was felt that an important point for study was that of the flame base lift distance. The variation in lift distance with varying parameters was of necessity divided into two parts; that concerning the initial flame, and that concerning the propagating flame. All lift distances were measured from the inner duct exit to the base of the flame.

The initial flame shall be considered first. Representative results of what was found are given in Figures 15, 16 and 17. In Figure 15 it is noted that increasing the inner gas stream temperature had a definite effect upon the lift distance, while increasing the fuel-air ratio of the outer stream made no appreciable change in this distance. It appeared during the experiment that the initial flame when first in existence (i.e. at the most lean operating condition) had a base that was somewhat higher than subsequent fuel richer flames. However, the initial flame on first appearance was so weak and the subsequent reduction in lift with increased F/A, if any, so small, that the techniques employed in measuring the lift did not permit positive identification of a change in lift distance. All points in Figure 15 subsequent to the leanest initial flame were unequivocally determined. The interesting feature presented in Figure 15 is the very low equivalence ratio ϕ, at which ignition was attained. For

the most part, no point corresponding to a lean blow-off could be obtained for this initial flame at any but minimum temperatures. The minimum equivalence ratio noted in Figure 15, except for $T_i = 1037°K$, was in each case the minimum that the equipment would meter.

A cross plot of Figure 15, together with some other available points, is presented in Figure 16. Several interesting points are incorporated in this figure. First, it shows that the lift distance variation of the initial flame decreased relatively smoothly with increasing inner air temperature. Secondly, the minimum ignition temperature, which is indicated as a straight line in Figure 16, appeared independent of relative duct velocities. Several minimum ignition temperatures were noted at various relative velocities and these did not vary by more than $\pm$ 2°C from 1027°K. The last important result presented in Figure 16 shows that the lift distance of the initial flame was asymptotically approaching a minimum, but not zero, with increasing T_i. The flame, in other words, did not directly attach itself to the inner duct rim. It was not possible to check the lift distance at a temperature in excess of 1313°K because the coil (Fig. 1) burned out after this reading was obtained.

Figure 17 is presented to illustrate that neither V_i nor V_o had any effect upon the lift distance of the initial flame. Variations in V_i and V_o, however, did affect the equivalence ratio which could be reached before blowback occurred but this was more properly associated with the propagating flame.

Reviewing the above, it may be said, then, that the only parameter which appeared to materially influence V_i, the lift distance

of the initial flame, was T_i.

The lift distance of the propagating flame, contrary to that of the initial flame, was found to be influenced by all four parameters, V_i, V_o, ϕ, and T_i. It was also noted (Figs. 18-21) that the distances involved were much greater than were those of the initial flame. Figure 18 presents the location of the propagating flame for several values of V_o, Figure 19 for several values of V_i, and Figure 20 for several values of T_i. Note in all three of these figures that the location varied linearly with equivalence ratio. Attempts were made in these data to establish zero lift distance by running each series of tests to blowback but reproducibility was very poor. The equivalence ratio for blowback varied so from day to day with varying atmospheric conditions that most of these points were discarded. The motion of the air in the test cell as a result of the exhaust fan also had its effects. When near blowback, the propagating flame was so close to the inner duct exit that slight pressure variations would cause it to blow back. In connection with blowback, it is to be mentioned that the phenomenon seemed associated only with the propagating flame. With increasing ϕ this flame moved down and swallowed the initial flame (Fig. 14) and then blowback occurred.

Figure 21 presents the variation in the lift distance of the propagating flame with temperature. This figure is a cross plot of Figure 20.

4. <u>Significance of Results.</u>

The process of ignition presented herein may be chiefly

thermal. The chemical content of a combustible mixture also enters as a factor since a quick check in the same annular duct showed that propane-air mixtures required higher temperatures for ignition to occur. It is recommended that several chemically different combustible mixtures be investigated and that ignition temperatures for these mixtures be obtained. These ignition temperatures may then be compared with those obtained by other methods to see if any correlation exists.

In view of the relationship between this investigation and the problem of flame holding mechanisms, it was felt that the most important of the flames observed was the initial flame. This flame was affected primarily by T_i. Furthermore, the initial flame found here exhibited no definite lean blowoff characteristics as found in flame holding behind a bluff body. This may be accounted for when one considers how the source of heat is provided behind a flame holding body as compared to the heat source in this investigation.

Behind a bluff body, the heat may be thought of as being manufactured. That is, the temperature of the gas recirculating behind a bluff body is dependent upon the reaction in and adjacent to this recirculating zone (Cf. Ref. 1). As the fuel-air mixture becomes more lean in such case, the temperature behind the bluff body drops until finally combustion can no longer be supported. In such cases, fuel-air ratio and velocity are important blow-off parameters. In the setup used in this investigation, however, a constant temperature was maintained in the inner stream regardless of the fuel-air ratio of the combustible mixture. Thus, the flame was not subject to

blow-off at lean mixture ratios. Somewhere in the mixing zone between the two parallel streams, there existed the right chemical ratio and sufficient heat to initiate combustion.

The lift distance of the initial flame may be ascribed to the time required for sufficient heat to reach the combustible mixture to produce ignition. With increased T_1 it naturally took less time to reach that temperature. The fact that the initial flame would not attach itself to the inner duct edge was probably due to the quenching effect of this cool surface. Extending Figure 16 beyond its present upper temperature limit would determine a minimum for this distance.

One might wonder at this point if the initial flame were not in fact a cool flame. This was not felt to be the case because all past visual investigations of cool flames have described them as having just a suggestion of form and color. The initial flame in this case was not a vigorous flame but it was certainly much more than a hazy indication that a reaction of some sort was taking place.

The base of the propagating flame may be considered as that point at which the gas stream velocities coincided with burning velocity. Since burning velocity increases with increasing mixture ratio, the propagating flame was able to move closer to the duct exit with higher fuel-air ratio. The burning velocity point of view also explains why the lift distance of the propagating flame was dependent upon V_1 and V_o.

The shape of the propagating flame was due to the divergence of the gas stream as it passed through the initial flame boundary.

Many authors have described this process and it will not be repeated here (Cf. Ref. 3, pp. 250-257).

The flashback observed in the investigation was associated with the propagating flame. As the fuel-air ratio was progressively increased, the burning velocity of the propagating flame increased. When the burning velocity exceeded the gas velocity, the combustion wave propagated against the gas stream into the tube.

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TABLE I

NOMENCLATURE

ε = thermocouple junction emissivity

ϕ = fuel-air equivalence ratio

F = form factor, see Appendix I

F/A = fuel-air ratio

p = pressure (lbs/in^2)

Q = volume flow rate (cc/sec)

Re = Reynolds number

T = temperature (degrees Kelvin)

T_i = temperature of inner duct

T_o = temperature of reflecting surface which thermocouple sees

V_i = velocity of gas in inner duct (cm/sec)

V_o = velocity of gas in outer duct (cm/sec)

Y = lift distance of propagating flame

Z = lift distance of initial flame

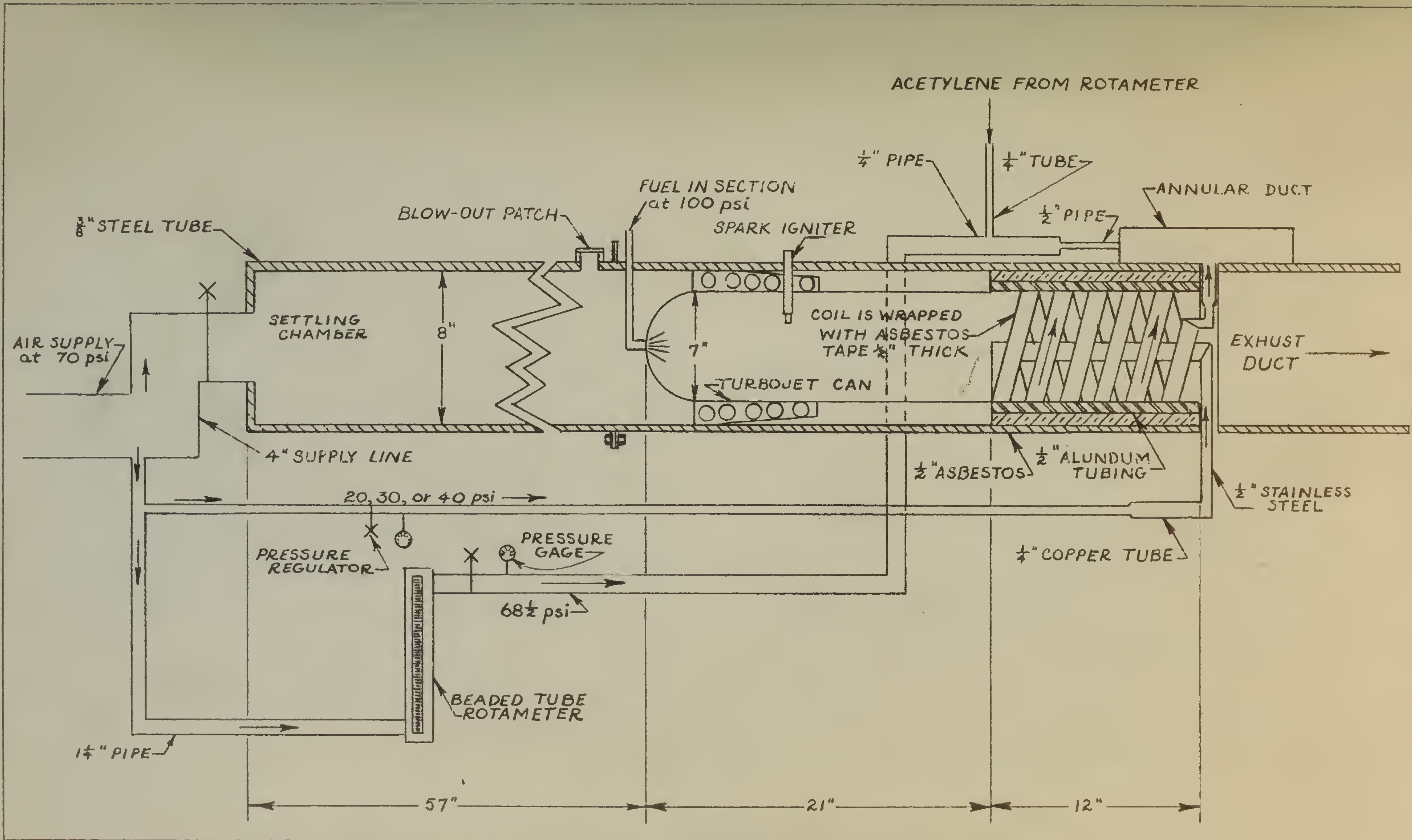


Figure 1. GENERAL SKETCH of PIPING and HEAT EXCHANGER LAYOUT

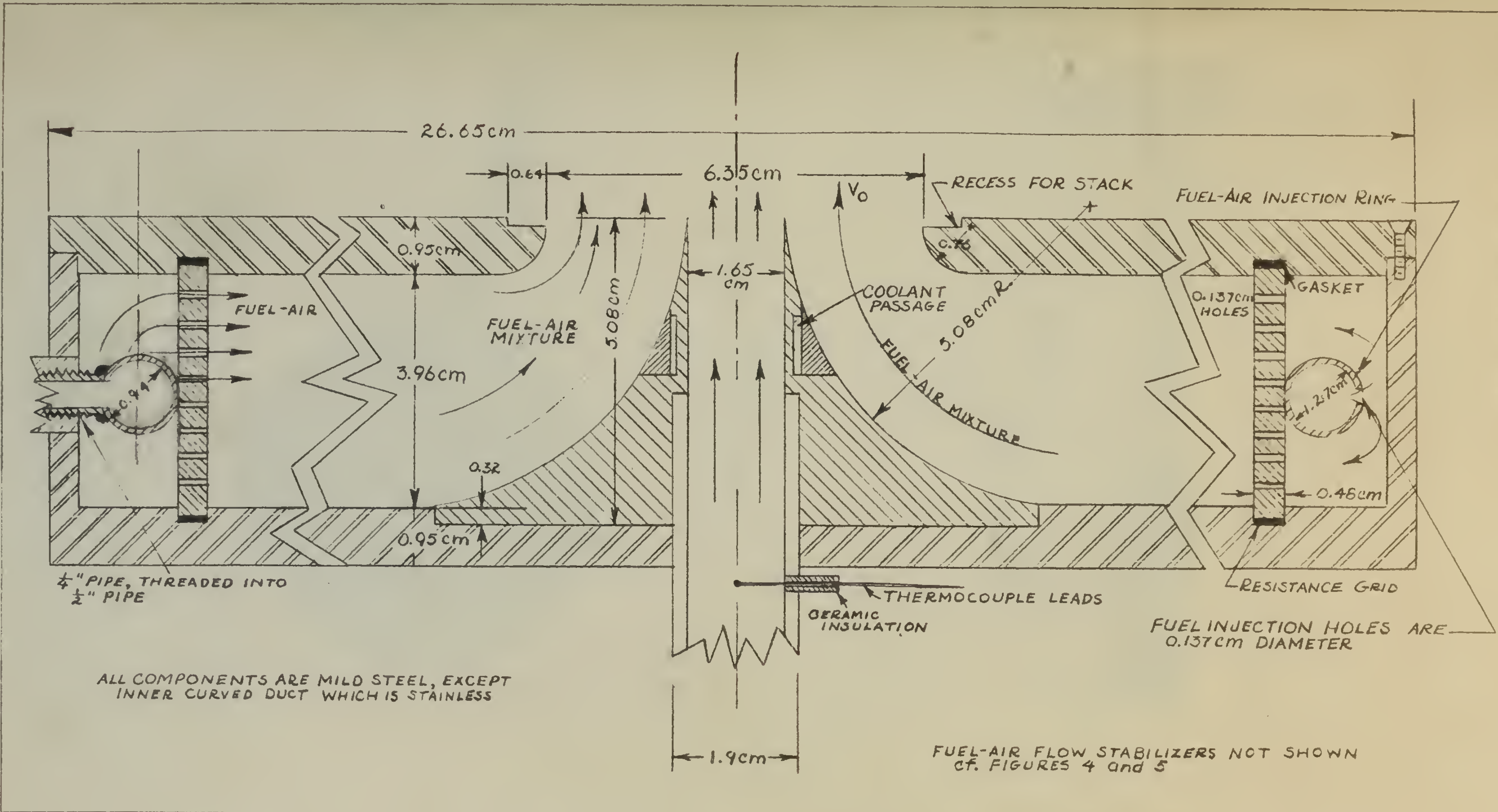


Figure 2. DETAILS OF THE ANNULAR DUCT

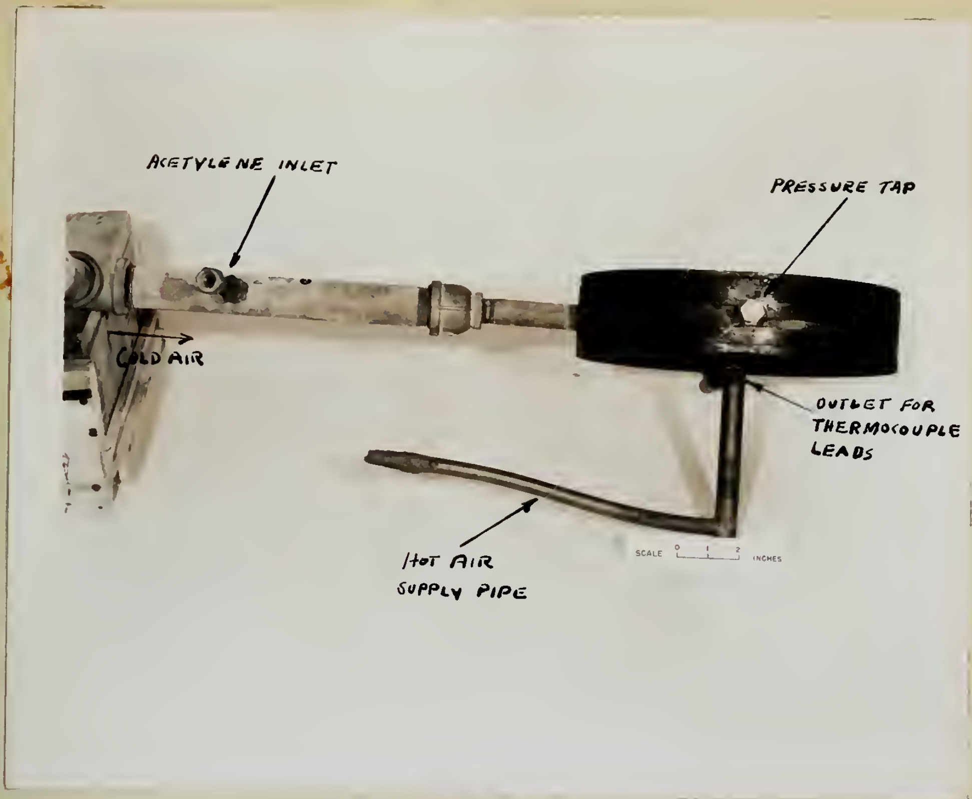


Figure 3
THE ANNULAR DUCT ASSEMBLED

Figure 4
TOP VIEW OF ANNULAR DUCT
(Top Plate Removed)

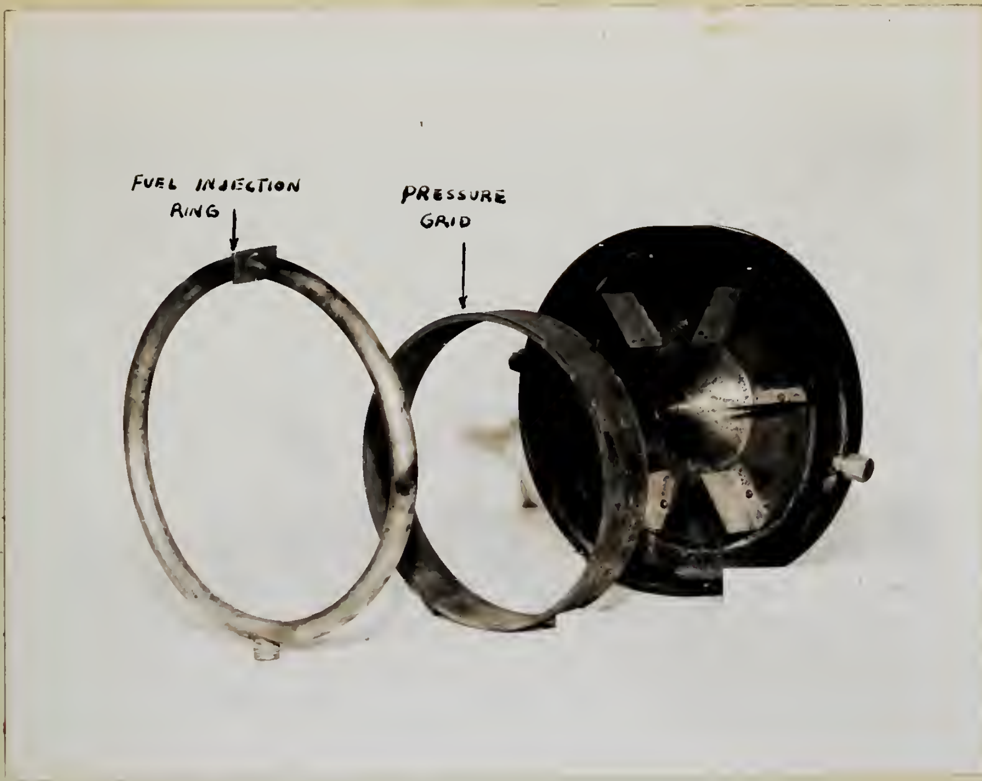


Figure 5
COMPONENTS OF THE ANNULAR DUCT

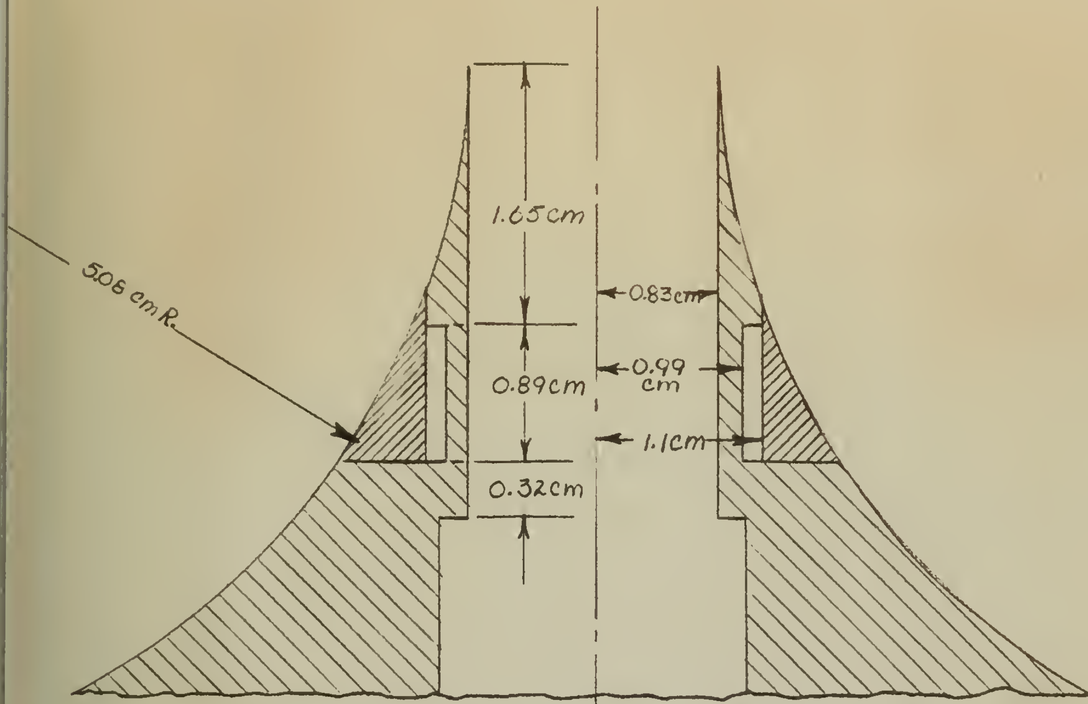


Figure 6. DETAILS of the INNER DUCT

Figure 7. VIEW of INNER DUCT

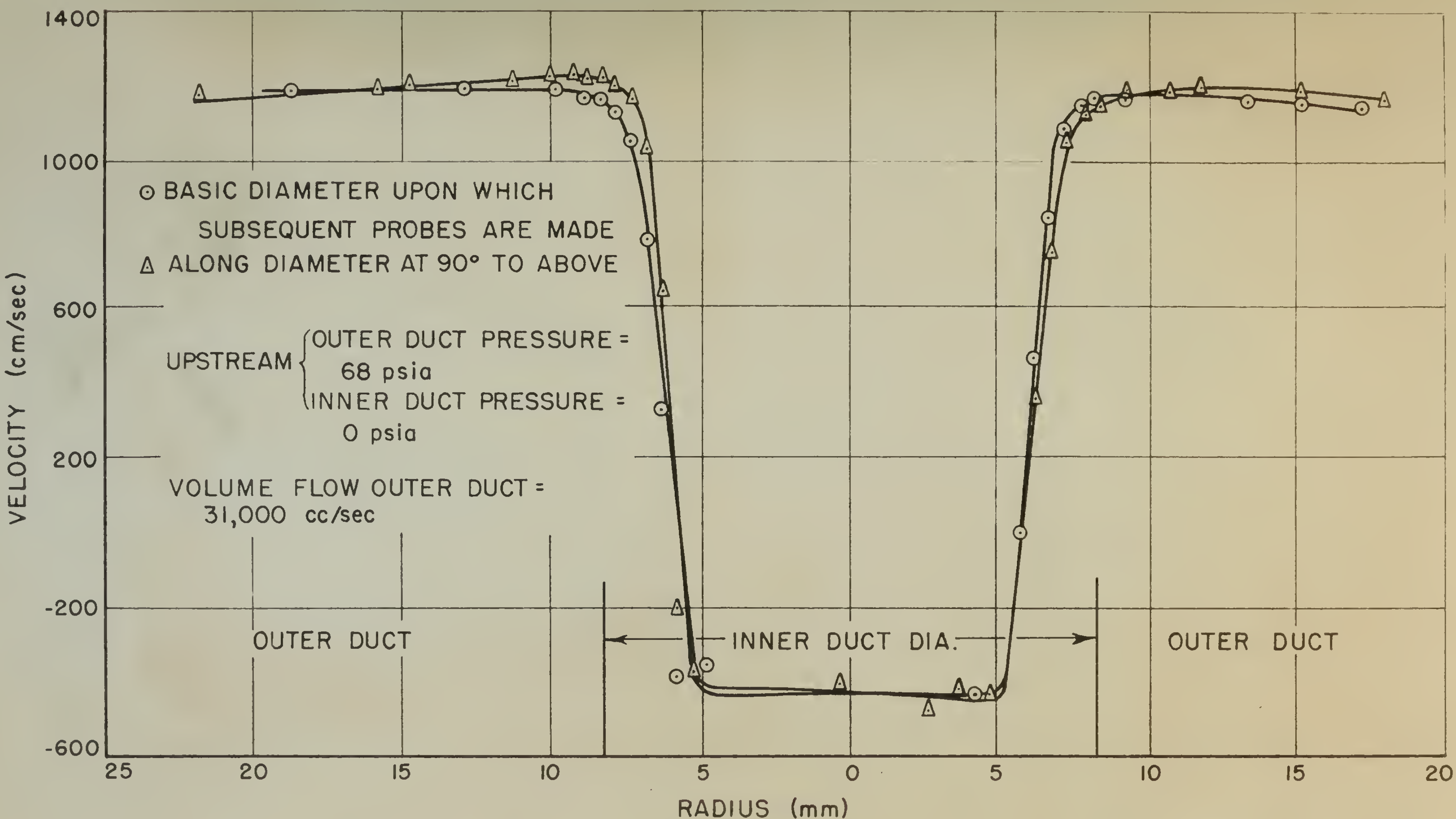


Figure 8. COLD VELOCITY PROBE ALONG DIAMETERS of DUCT

Figure 9. COLD VELOCITY SURVEY ALONG DIAMETERS OF DUCT

UPSTREAM { OUTER DUCT SUPPLY PRESSURE = 68 psia; INNER DUCT SUPPLY PRESSURE = 20 psia }

VOLUME FLOW OUTER DUCT = 31,000 cc/sec

(HORIZONTAL DISPLACEMENT OF CURVES BELIEVED DUE TO INACCURACY IN DETERMINING INNER DUCT EDGE)

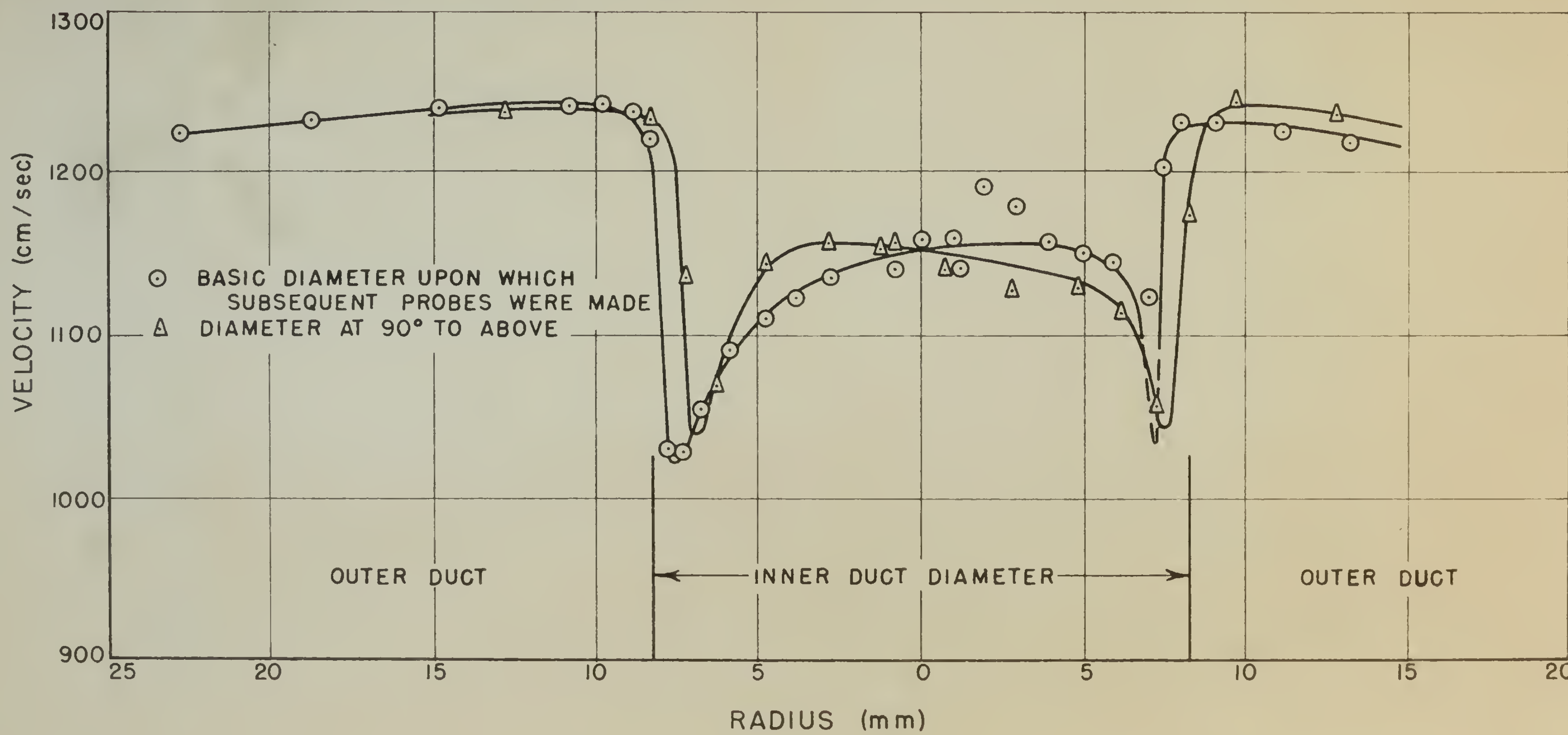
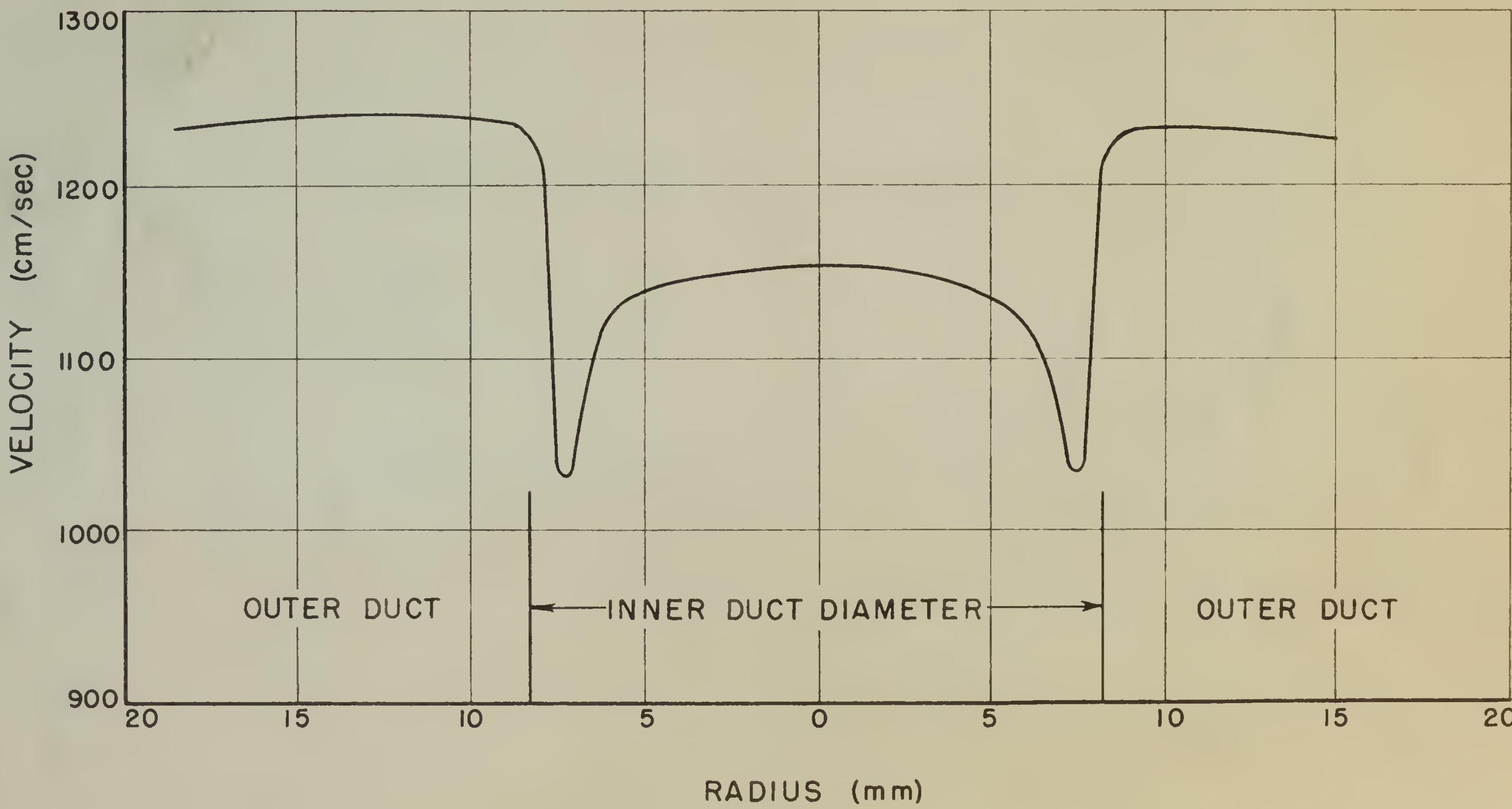


Figure 10. MEAN COLD VELOCITY PROFILE

OUTER DUCT SUPPLY PRESSURE = 68 psi
INNER DUCT SUPPLY PRESSURE = 20 psi



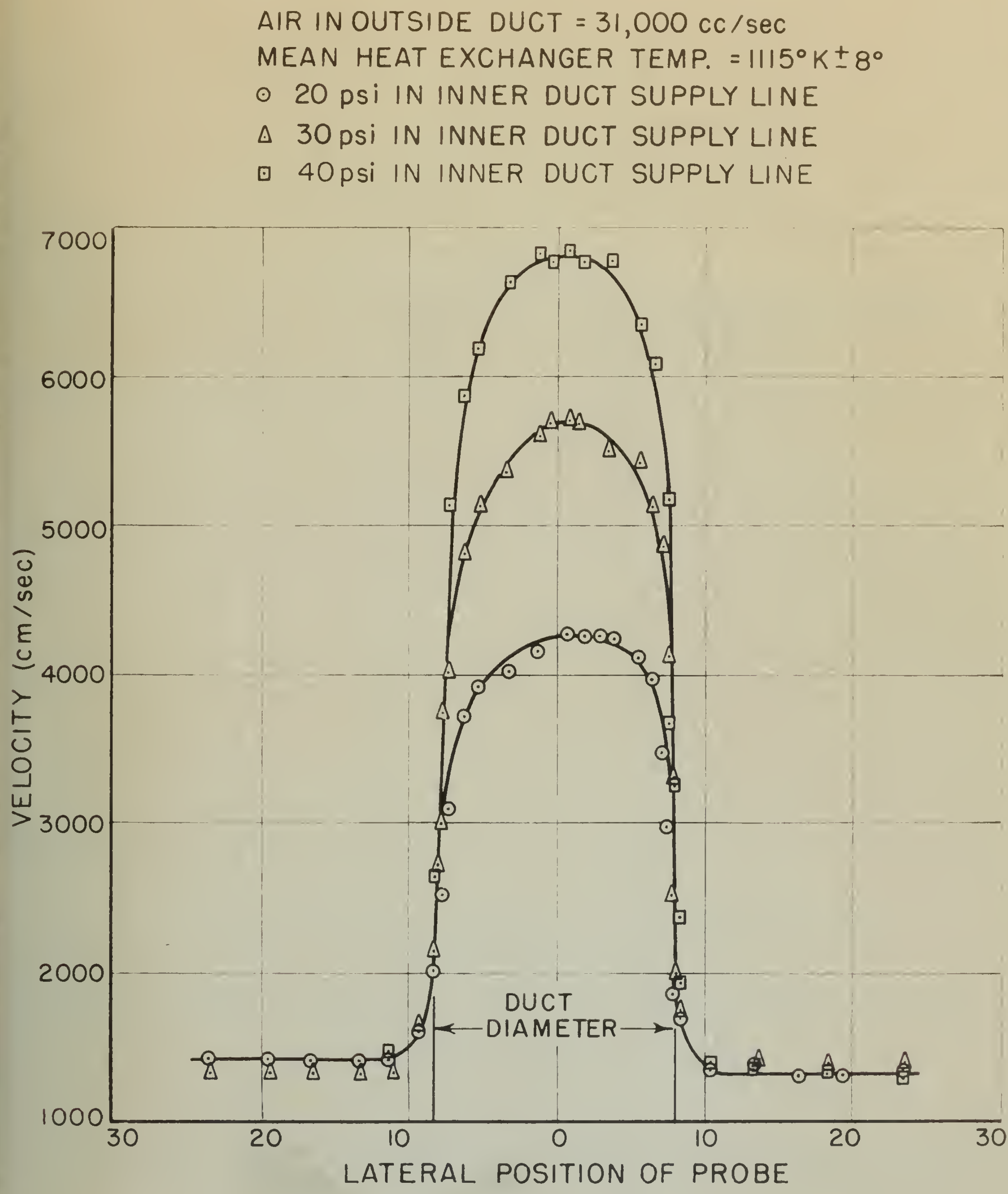


Figure II. VELOCITY PROFILE at a POINT 0.75-mm ABOVE INNER DUCT EXIT

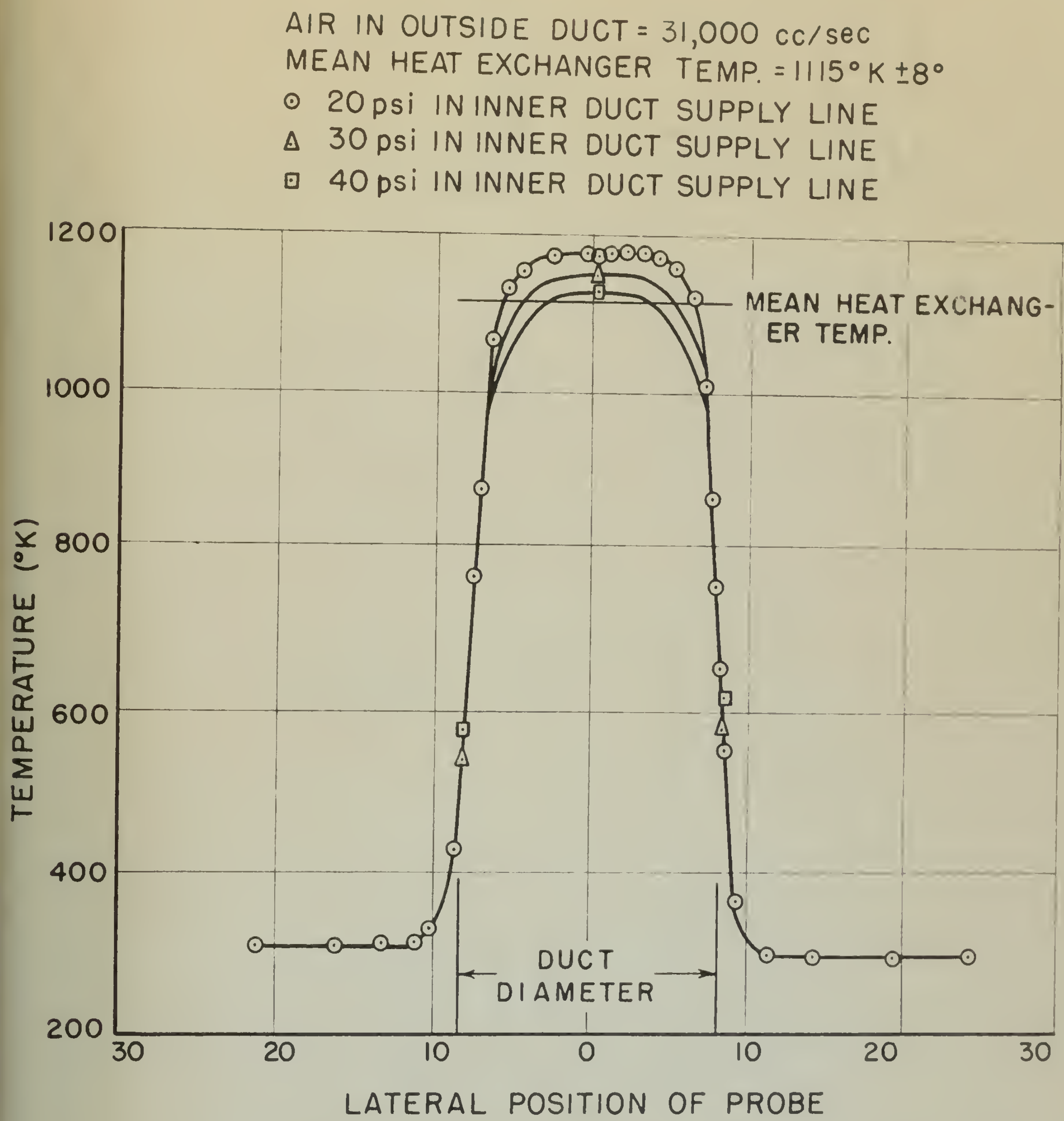
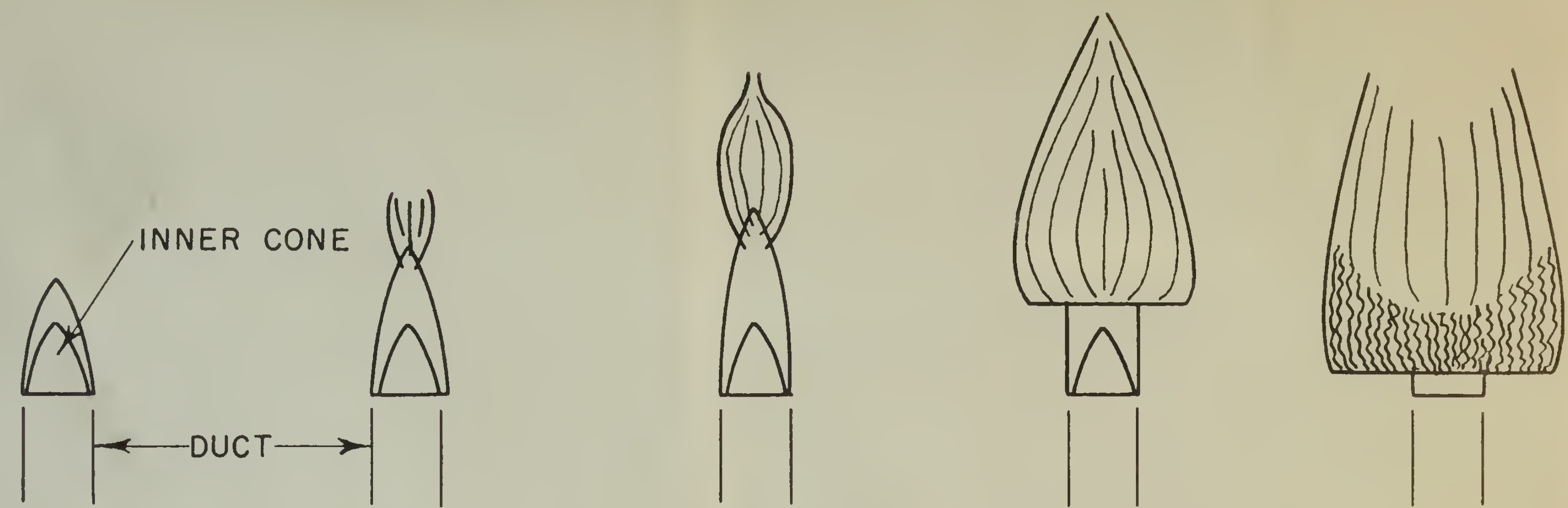


Figure 12. TRUE TEMPERATURE PROFILE at a POINT 0.75-mm ABOVE INNER DUCT EXIT



a. INITIAL FLAME

b. FIRST APPEARANCE OF PROPAGATING FLAME

c. PROPAGATING FLAME STRONGER AND CLOSER TO DUCT EXIT

d. PROPAGATING FLAME BUILDS IN INTENSITY. NO NOTICEABLE CHANGE IN INITIAL FLAME FROM FIRST OBSERVATION

e. JUST PRIOR TO BLOW-BACK. PROPAGATING FLAME VERY INTENSE, INITIAL FLAME ALMOST SWALLOWED

Figure 13. STAGES of FLAME as F/A WAS INCREASED

Figure 14

a. Propagating and initial flame. Initial flame is pencil like protuberance below body of flame. (T_i = 1118, V_o = 8.5 M/sec, V_i = 45 M/sec, ϕ = .3202.) Ignition in this case occurred for ϕ = .182.

b. Propagating flame just before blowback. Same conditions existed as in (a) except that ϕ = .521.

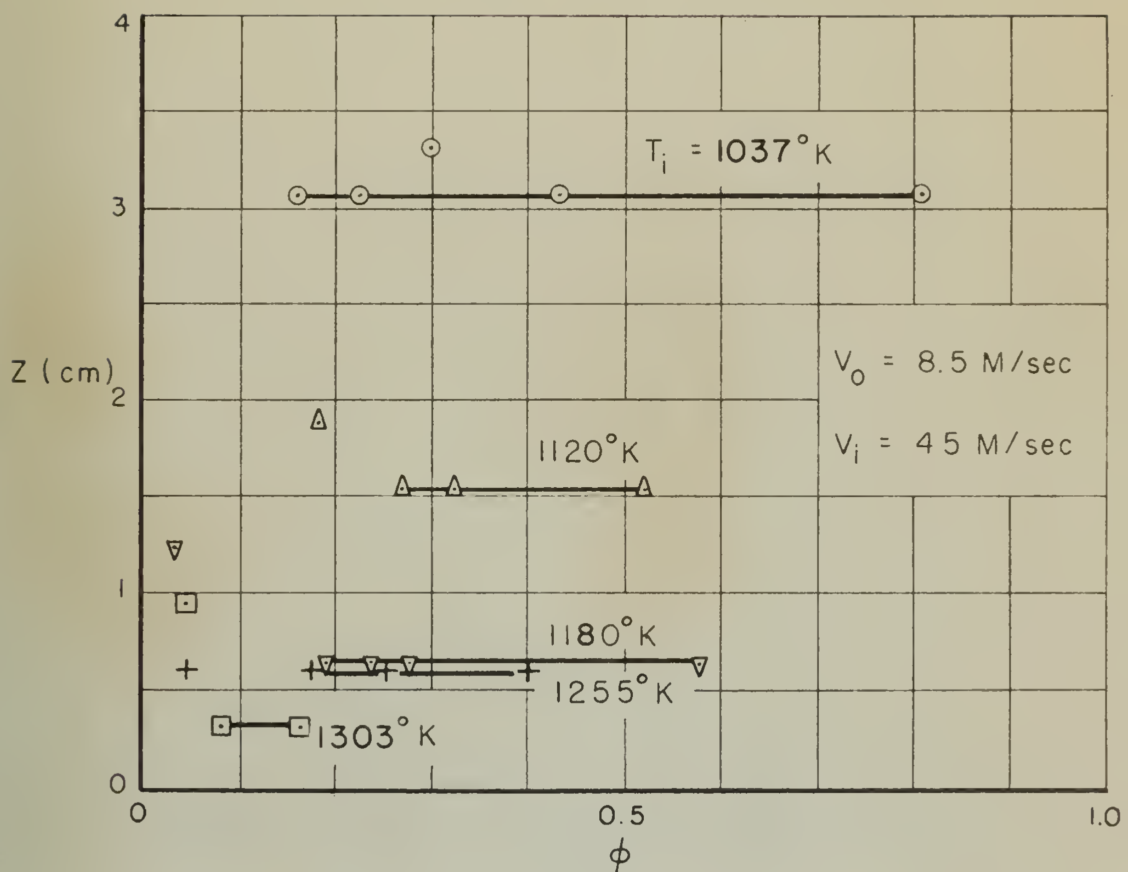


Figure 15. POSITION OF INITIAL FLAME
VS.
FUEL-AIR EQUIVALENCE RATIO ϕ

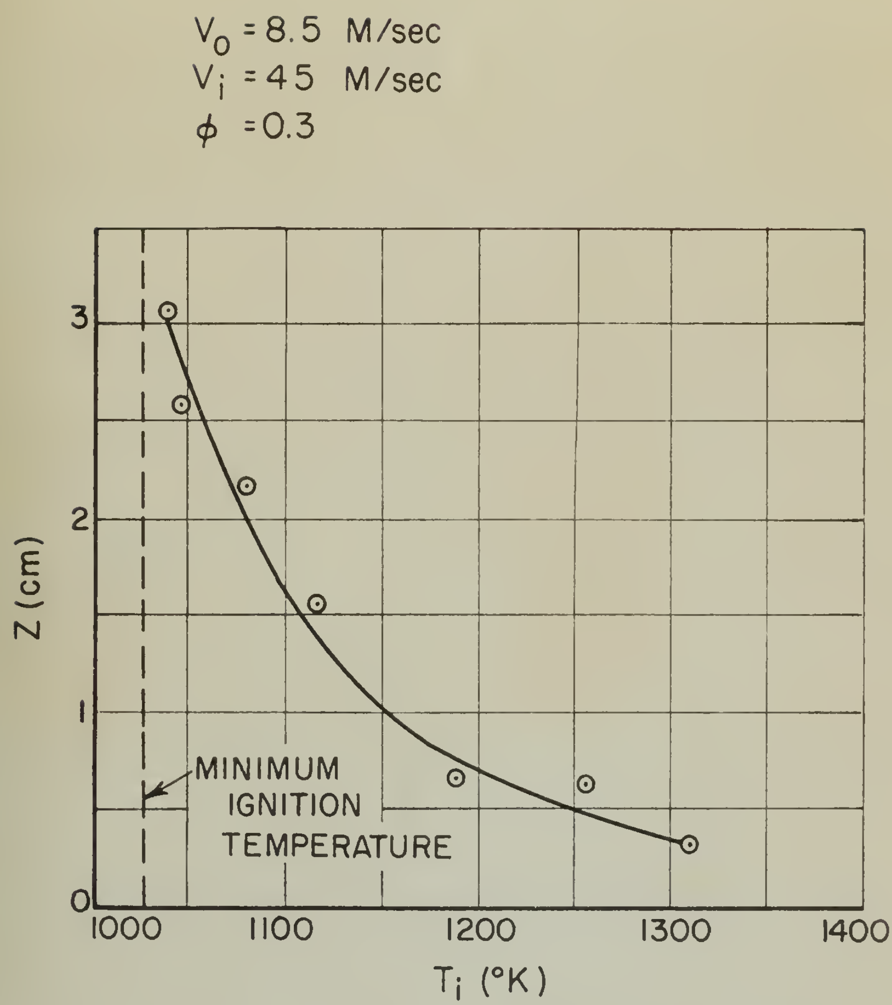


Figure 16. POSITION of INITIAL FLAME vs TEMPERATURE of INNER STREAM

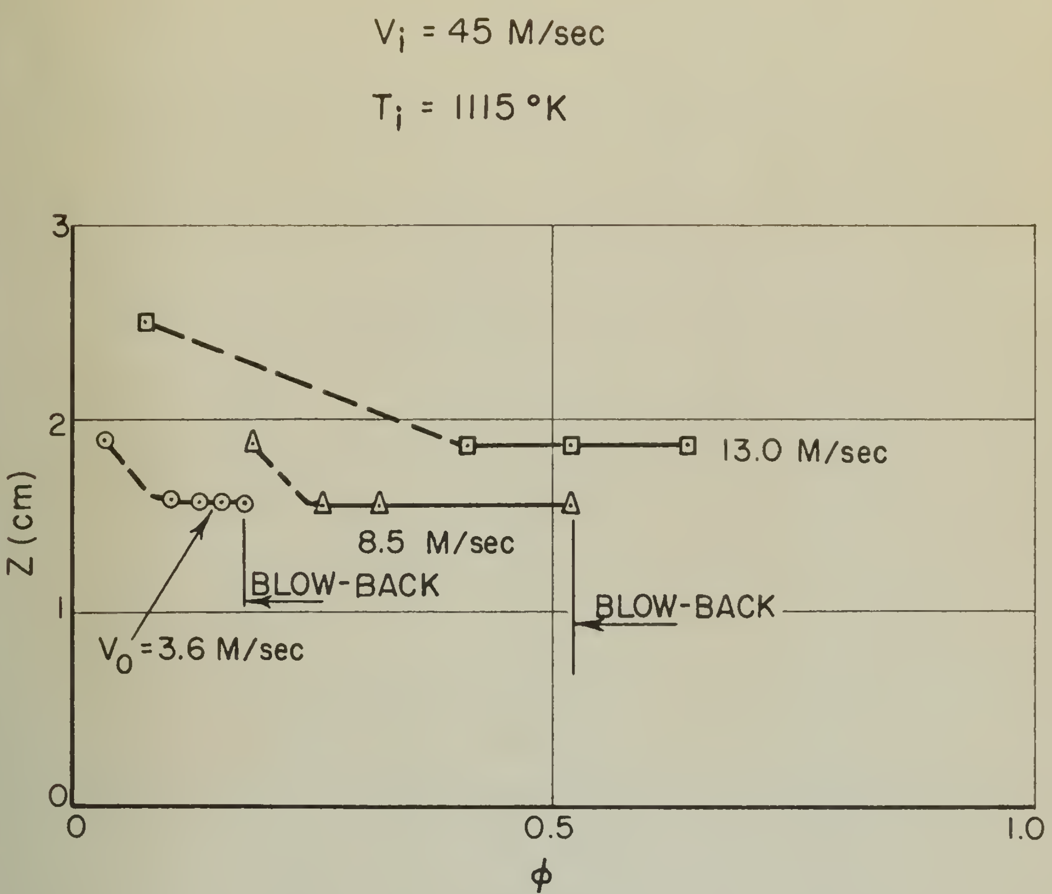
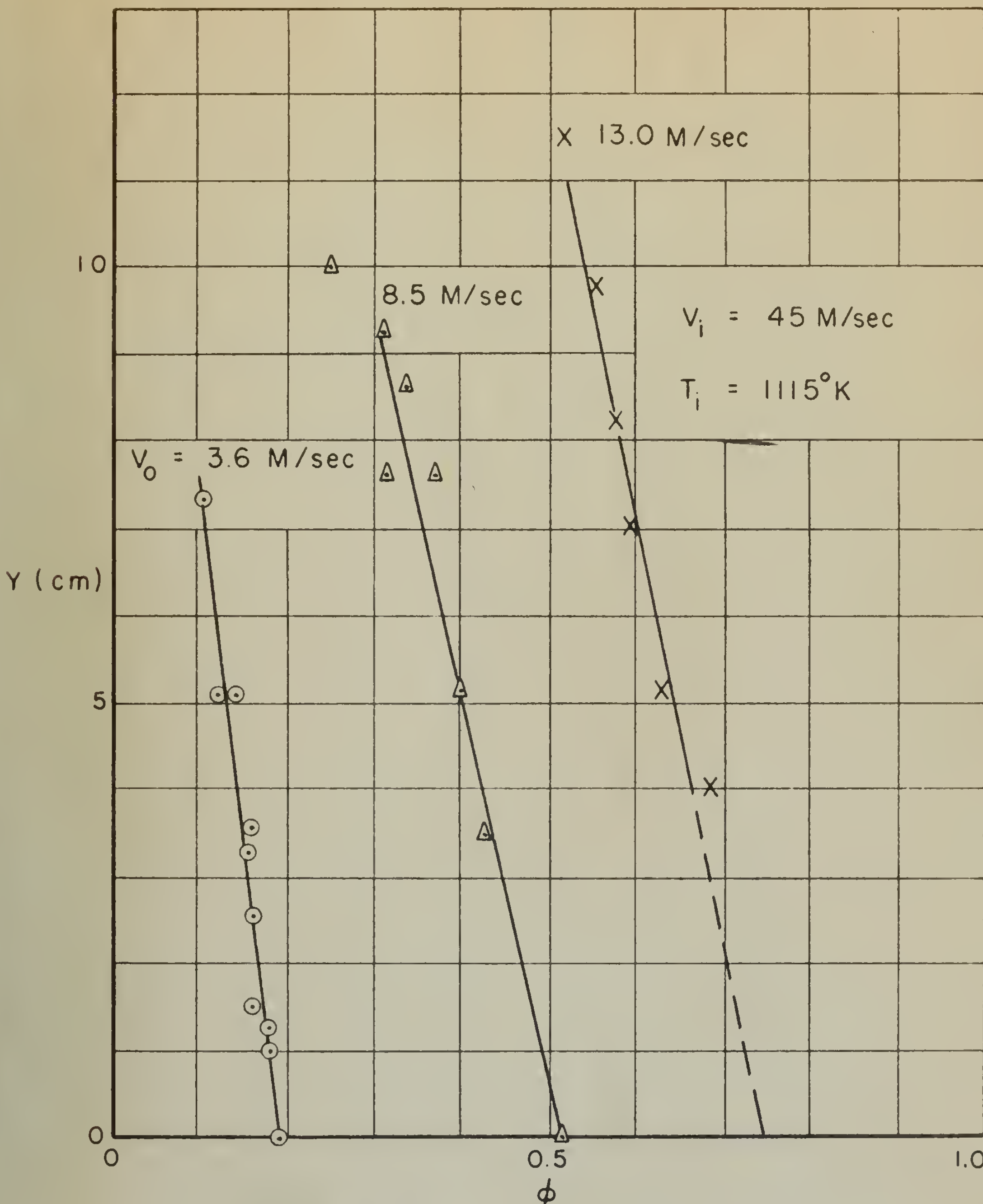


Figure 17. POSITION of INITIAL FLAME FOR SEVERAL VELOCITIES of the OUTER STREAM



LOCATION OF PROPAGATING FLAME FOR SEVERAL VELOCITIES OF THE OUTER STREAM

FIG. 18

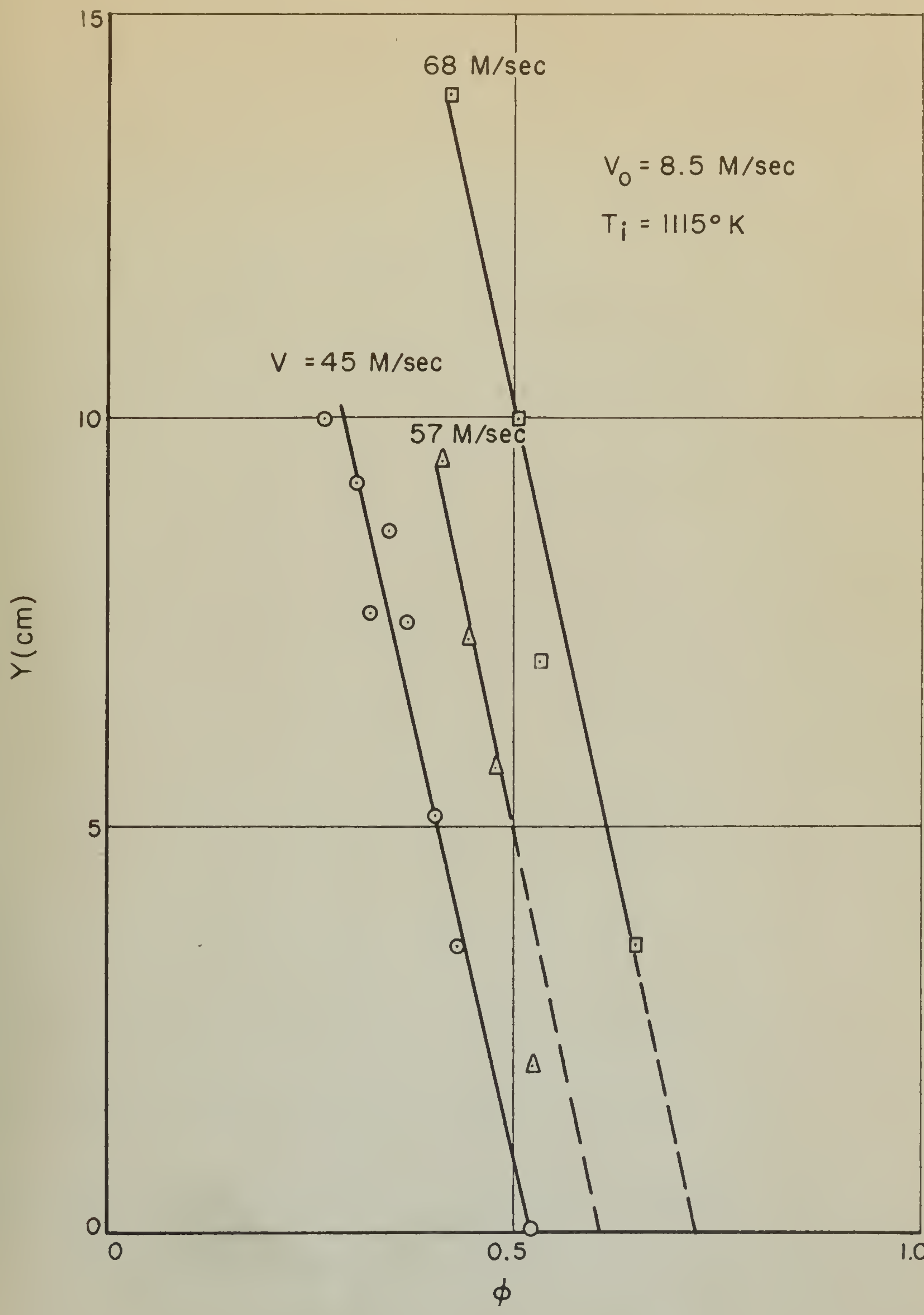
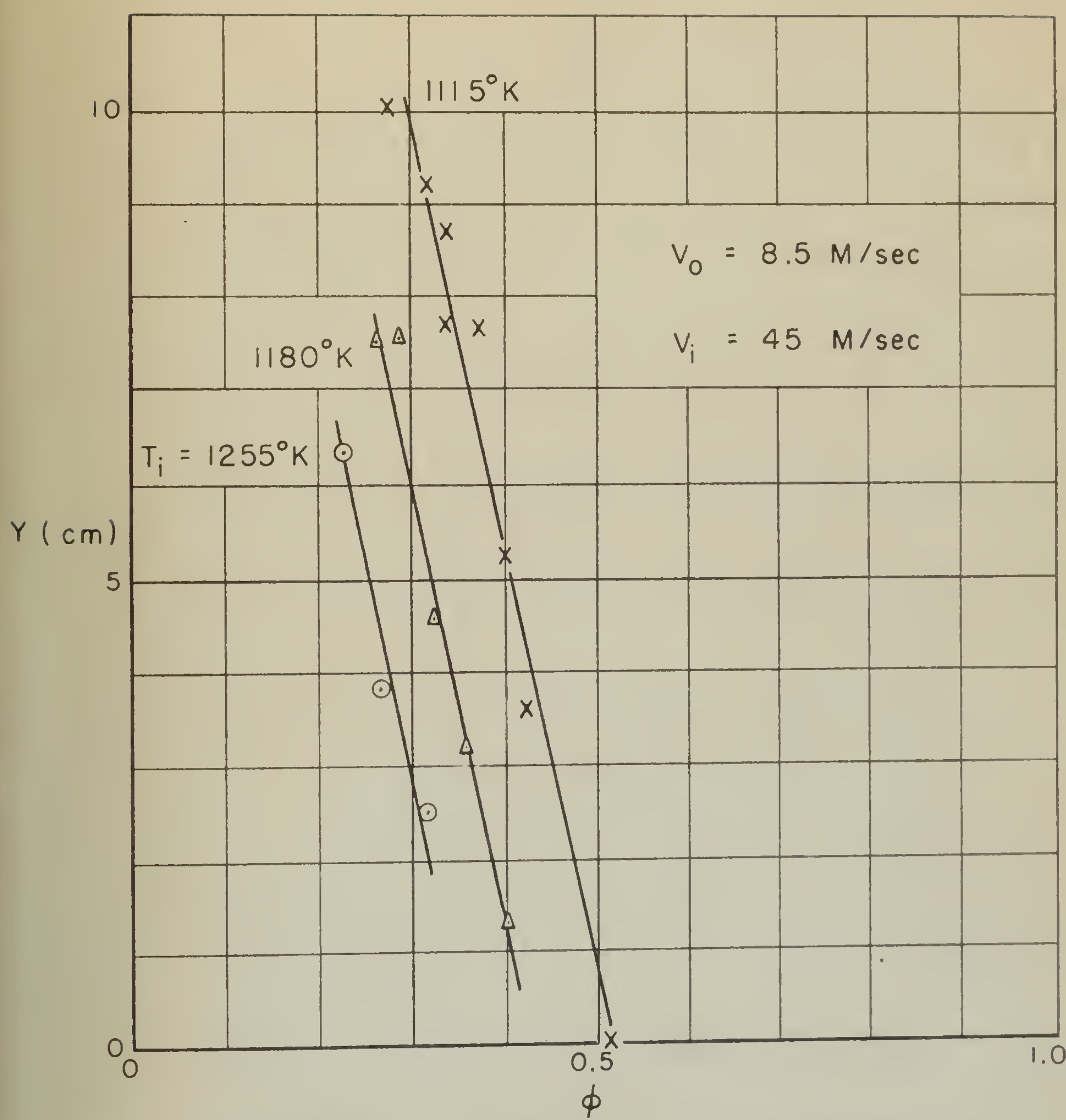


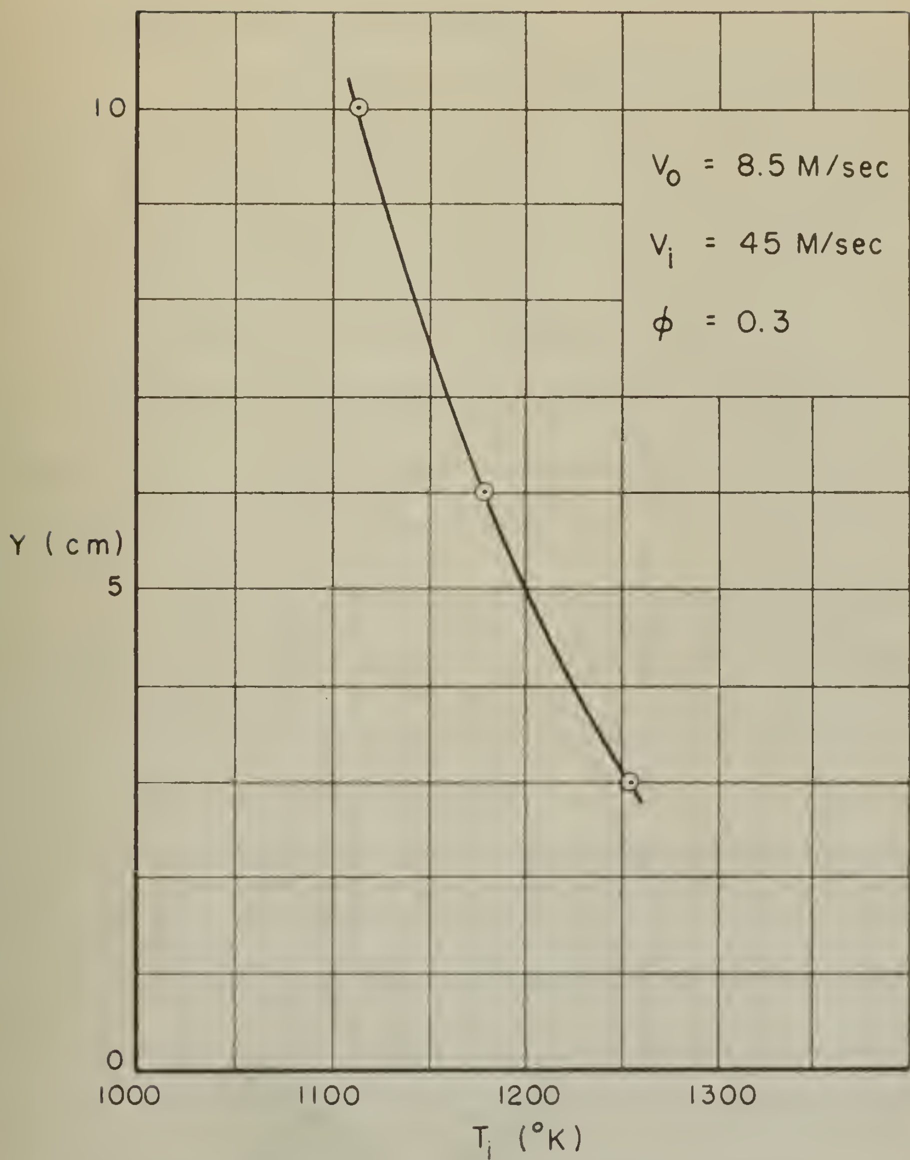
Figure 19. LOCATION of PROPAGATING FLAME for SEVERAL VELOCITIES of the INNER STREAM



LOCATION OF PROPAGATING FLAME FOR SEVERAL INNER STREAM TEMPERATURES

FIG. 20

FIG. 21



LOCATION OF PROPAGATING FLAME
VS.
TEMPERATURE OF INNER STREAM

APPENDIX I

A TECHNIQUE FOR THE MEASUREMENT OF THE TRUE TEMPERATURE OF A GAS FROM THERMOCOUPLE READINGS

1. Thermo Electric Thermometry.

The reproducibility of thermocouple temperatures depends upon the physical condition of the metal. Thermocouple materials can be selected and matched to yield $\pm$ 3/4% at high temperatures. Long-time exposure of a thermocouple to high temperature causes the emf corresponding to a given temperature to increase, or the temperature corresponding to a given emf to decrease. The maximum change in calibration for Chromel-Alumel thermocouples at 1500°K after 200 hours is $\pm$ 11.7°C (Ref. 1, p. 1259).

The bare thermocouple junction receives heat by thermal condition, and smaller amounts by radiation and convection. The junction loses heat by conduction along wires, and by convection, conduction, and radiation to surroundings.

The radiation error of a thermocouple decreases as the size of the wire is decreased because of the existence of a gas film. Because of this film, the area receiving convection heat from the gas is larger than the area (actual surface) of the thermocouple which is radiating through the surface film. On this basis, a wire of zero diameter would give the true gas temperature.

The following presents some pertinent details of thermocouple junction materials:

Type Thermocouple	Usual Temperature Range	Maximum Temperature
Platinum to Platinum-Rhodium	0 - 1450°C	1700°C
Chromel Alumel	-200 to 1200	1350
Iron to Constantan	-200 to 750	1000

The chromel alumel thermocouple is 95% Ni, the melting point of Ni being 1455°C. This material was selected for use in the thermal combustion investigation because it is less sensitive to catalysis than platinum to platinum-rhodium. For the particular application in which used, this advantage outweighs the higher temperature range at which platinum to platinum-rhodium thermocouples may be used.

2. Development of the Technique.

McAdams (Ref. 2) presents a basic technique for the calculation of the true temperature of a gas, the presentation developing from a heat balance. The basic method, however, is rather lengthy. Taking advantage of some recent information available from the National Bureau of Standards (Ref. 3) and F. G. Keyes (Ref. 4), McAdams's presentation is extended to give for certain specific applications, a more rapid means of correcting thermocouple readings to true gas temperature.

The following applies only to a thermocouple in a hot stream of air but above references contain sufficient information to duplicate the following in many other gases frequently employed in combustion research.

To compute the true temperature of a gas from the reading of a thermocouple placed in a gas stream and in sight of surrounding walls that may be at various temperatures a heat balance is used:

$$q_{gr} + q_c = q_k + q_r$$

where q_{gr} is the rate of heat flow between gas and thermocouple by the mechanism of gas radiation, q_c is the rate of heat flow between gas and thermocouple by convection, q_r is the sum of the various terms representing the radiant heat interchange between the thermocouple and various surfaces that it sees, q_k is the heat conducted from the thermocouple to the walls confining the gas stream. (Ref. 1).

q_k, the conduction through the leads from the thermocouple is made negligible by keeping the leads hot and close to thermocouple temperature. q_{gr} is likewise negligible in comparison to q_c and q_r since gases with symmetrical molecules have been found "not to show absorption bands in those wave-length regions of importance in radiant-heat transmission at temperatures met in industrial practice". (Ref. 1, p. 64).

The equation at equilibrium therefore reduces to:

Heat gained by thermocouple in hot gas stream through conduction = Heat lost by thermocouple in hot gas stream through radiation, or

$$hS(T_g - T) = \sigma \varepsilon F S(T^4 - T_o^4) \qquad (1)$$

where

h = coefficient of forced convective heat transfer

S = surface area of thermocouple

T_g = temperature of gas stream °K

T = temperature of thermocouple °K

σ = radiation constant = 5.735×10^{-5} $\dfrac{\text{erg}}{\text{cm}^2\ {}^\circ\text{K}^4\ \text{sec}}$

$$= 1.370 \times 10^{-12} \quad \frac{}{\text{cm}^2\ {}^\circ\text{K}^4\ \text{sec}}$$

ε = emissivity of thermocouple

F = form factor to account for variations in temperature of surroundings

T_o = temperature of surroundings

In the formula above, h is the only unknown other than the temperature. Now, Nu (Nusselt No.) = $\frac{hD}{k}$ where

D = diameter of thermocouple

k = thermal conductivity in cal/sec cm °C.

From Reference 1, p. 222, for cylinders in air and diatomic gases:

$$\begin{aligned} Nu &= (Pr)^{.3}\ 0.26(Re)^{.6} \qquad 10^3 \le Re \le 5 \times 10^4 \\ &= (Pr)^{.3}\ 0.35 + 0.47(Re)^{.52} \qquad .1 \le Re \le 10^3 \end{aligned} \tag{2}$$

However, for heat transfer between air and spheres where $20 \le Re \le 15 \times 10^4$,

Pr assumed constant at .74, $\frac{hD}{k} = .33(Re)^{0.6}$ (Ref. 1, p. 237) (3)

We are confining ourselves to applications wherein spherical or bead thermocouples are employed. Further, McAdams assumed a constant Prandtl number for his determination of Nu for spherical objects but references 3 and 4 present excellent information on the variation

of Pr with temperature. To permit incorporating this information into our calculations a formula for Nu for heat transfer between air and spheres is manufactured from formulas (2) and (3) by retaining the term $(Re)^{0.6}$ and adjusting the constant of (2) so that for the special case where Pr = .74, equation (3) is obtained.

A reasonable equation for heat transfer between air and spheres therefore appears to be:

$$Nu = (Pr)^{.3} \; 0.36(Re)^{.6} \qquad (4)$$

where all evaluations are made at film temperature, T_f.

$$T_f = T + 1/2(T_g - T)$$

$$Pr = \frac{C_p \eta}{k} = \text{Prandtl's number} \qquad (5)$$

$$Re = \rho UD/\eta = \text{Reynolds' number} \qquad (6)$$

where:

C_p = heat capacity at constant pressure

η = viscosity (poises) (g/cm-sec)

k = thermal conductivity (cal/sec-cm °C)

U = velocity (cm/sec)

D = diameter of thermocouple (cm)

ρ = density (perfect gas law is employed for determination of this value)

Keyes, Reference 4, has produced empirical formulae for viscosity and thermal conductivity:

$$10^5 \eta = \frac{a_o \sqrt{T}}{1 + \frac{a}{T(10)^{a_1/T}}} \qquad 10^5 k = \frac{C_o \sqrt{T}}{1 + \frac{C}{T(10)^{C_1/T}}}$$

where for air the values of the constants are:

a_o	a	a_1	Temperature Range °K
1.4888	122.1	5.0	90 - 1845
C_o	C	C_1	
0.632	245.0	12	90 - 584

The National Bureau of Standards has also conducted recent surveys in the field of thermal properties of gases (Ref. 3). This data agrees very closely with that of Keyes' empirical formulae.

Using National Bureau of Standards' Tables augmented by Keyes' formulae, curves of viscosity and conductivity of air vs film temperature are made up (Fig. 1).

With the results of Figure 1, a plot of Prandtl numbers vs film temperature is made (Fig. 2) from formula (5). Where possible all calculations employed in developing this curve were made with National Bureau of Standards data. Above 1000°K, however, it was necessary to use Keyes' formula for k. The regions in which the above applies are noted in Figure 2.

The next set of curves to be developed are those for Reynolds' number (Fig. 3). These curves are computed from formula (6) for U = 100 cm/sec and for thermocouple diameters of 0.015, 0.03, and 0.1 cms.

Using formula (4) curves of Nu vs temperature may now be obtained (Fig. 4). h is thus readily determined from the definition of Nu.

Since Nu is given in Figure 4 for a gas velocity of 100 cm/sec only, a correction curve (Fig. 5) is supplied for velocities differing from 100 cm/sec. This curve is actually a correction to Re but is applied more easily as a correction to Nu. The curve is based on a multiplying factor of 1 for U = 100 cm/sec.

As a final aid in the computation of true gas temperature, the right side of equation (1), omitting ε and F, is presented in Figure 6 for the case where the thermocouple sees surfaces at atmospheric temperature, or $T_o = 300°K$.

3. Use of Curves to Problems in Gas Temperature Determination.

The true gas temperature calculation will be one of trial and error. Having T from the thermocouple reading, an estimate of T_g is made. This permits one to calculate h from formula (1), when proper ε and F are used. Figure 6 is an assistance in this calculation. With the estimated T_g and known T, T_f is determined. Entering Figure 4 with T_f and correcting as necessary with Figure 5, Nu is determined. Nu and the data in Figure 1 lead to the calculation of a second h since $Nu = \frac{hD}{k}$. When h as calculated from formula (1) equals that calculated from the above, the true gas temperature T_g will have been determined. A few applications of the method will soon permit one to determine T_g true with not more than two approximations to T_g.

4. Emissivity and Form Factor.

Two quantities in this method have not yet been discussed, namely, the emissivity, ε, and the form factor F. The form factor is readily determined from the geometry of the installation. The percentage of the total thermocouple surface that sees a reflecting surface at T_0, determines the value of F.

The emissivity is not so simply handled. From Reference 1, confining ourselves to chromel-alumel thermocouples since it was this material exclusively that was used in temperature measurements for the thermal combustion project conducted at the Jet Propulsion Laboratory, we find:

emissivity of chromel P unoxidized = 0.35

emissivity of alumel unoxidized = 0.37

emissivity of chromel P oxidized = 0.87

emissivity of alumel oxidized = 0.87

ε may thus have a wide range of values depending upon the state of oxidation of the thermocouple junction. Much work has been conducted on this subject at the Jet Propulsion Laboratory. A private communication from Mitchell Gilbert of the Jet Propulsion Laboratory further states that it is inadvisable to try to predict an intermediate value of ε. Either the low value for an unoxidized thermocouple of 0.36 should be used, or the completely oxidized value of 0.87 should be used. If the thermocouple has been subjected to high temperature for even a few hours (1 or 2) it is recommended that 0.87 be used. The answer, of course, is to insure constant ε by oxidizing the thermocouple junction as completely as possible before use. Four hours at high temperature is recommended as a minimum.

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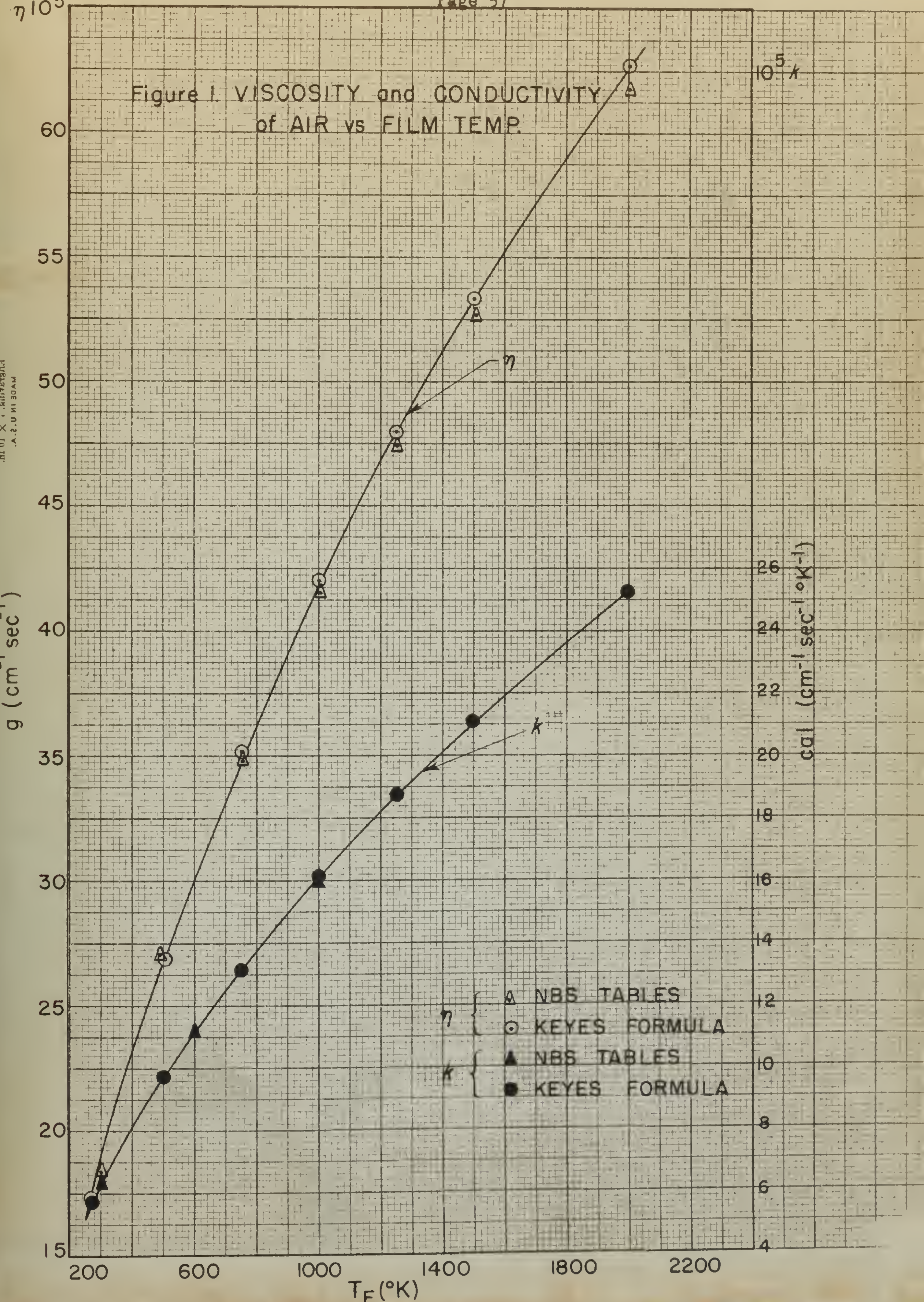

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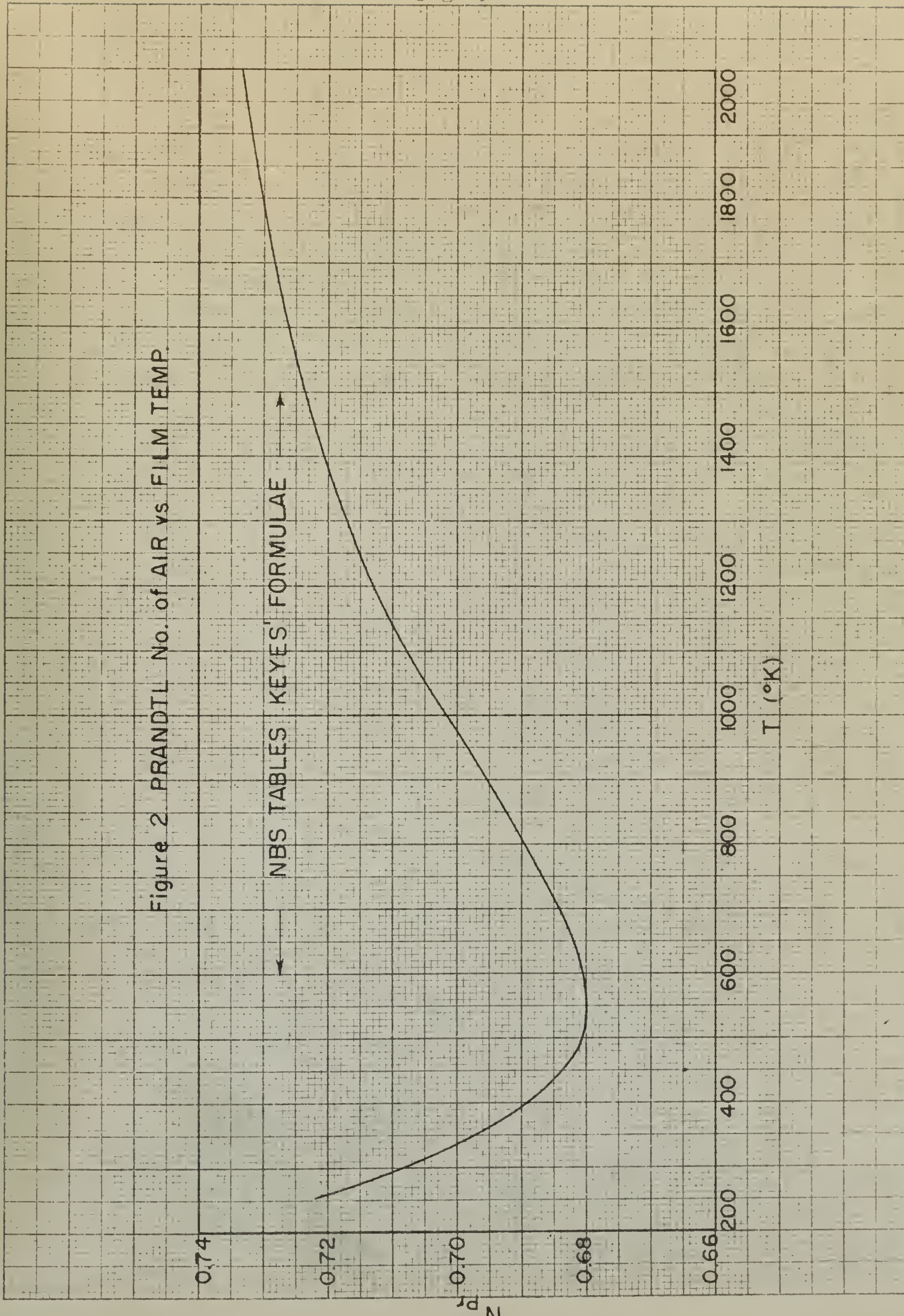


Figure 2 PRANDTL No. of AIR vs FILM TEMP.

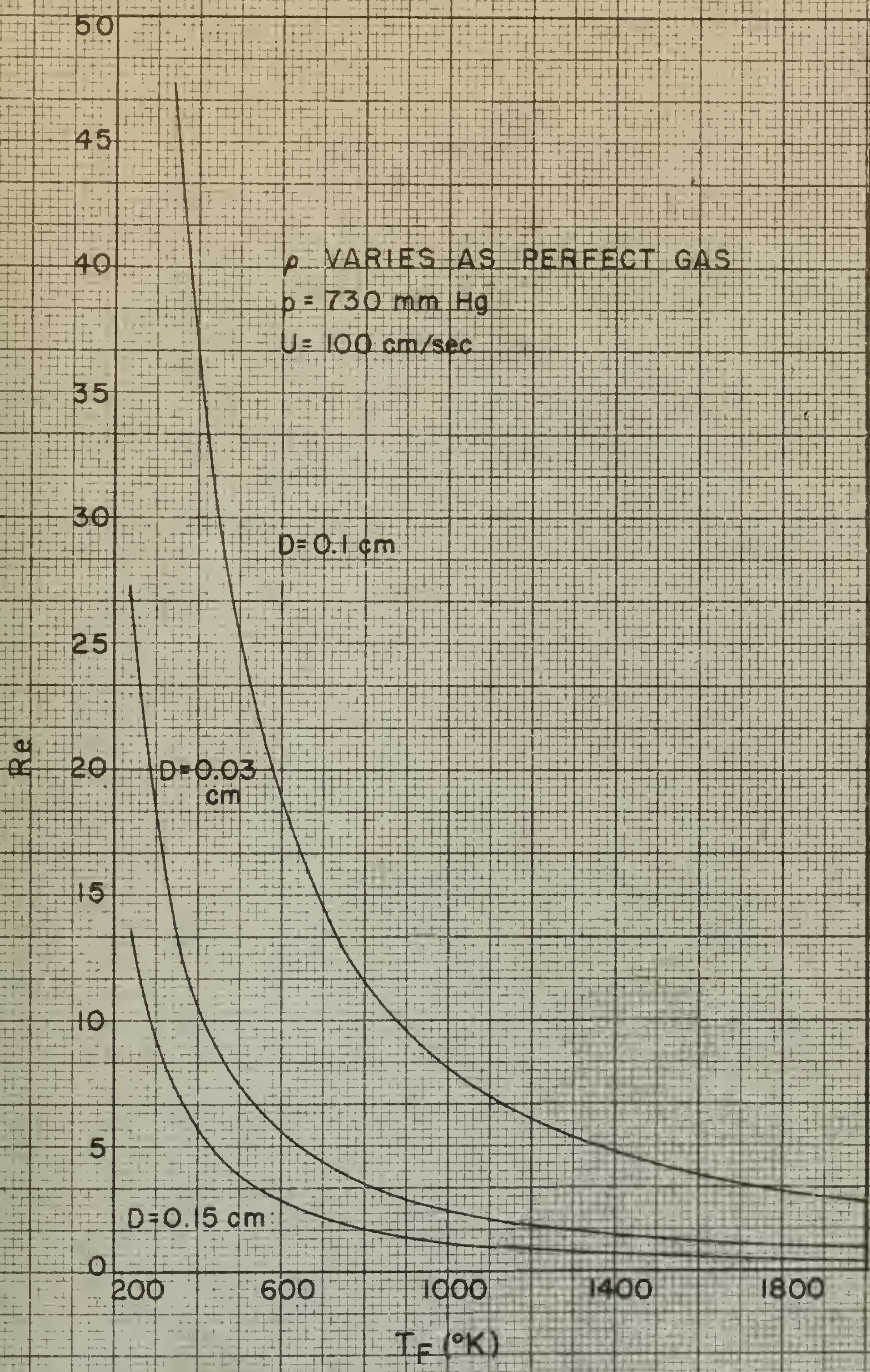


Figure 3. REYNOLDS No. for SPHERICAL OBJECT in AIR vs FILM TEMPERATURE

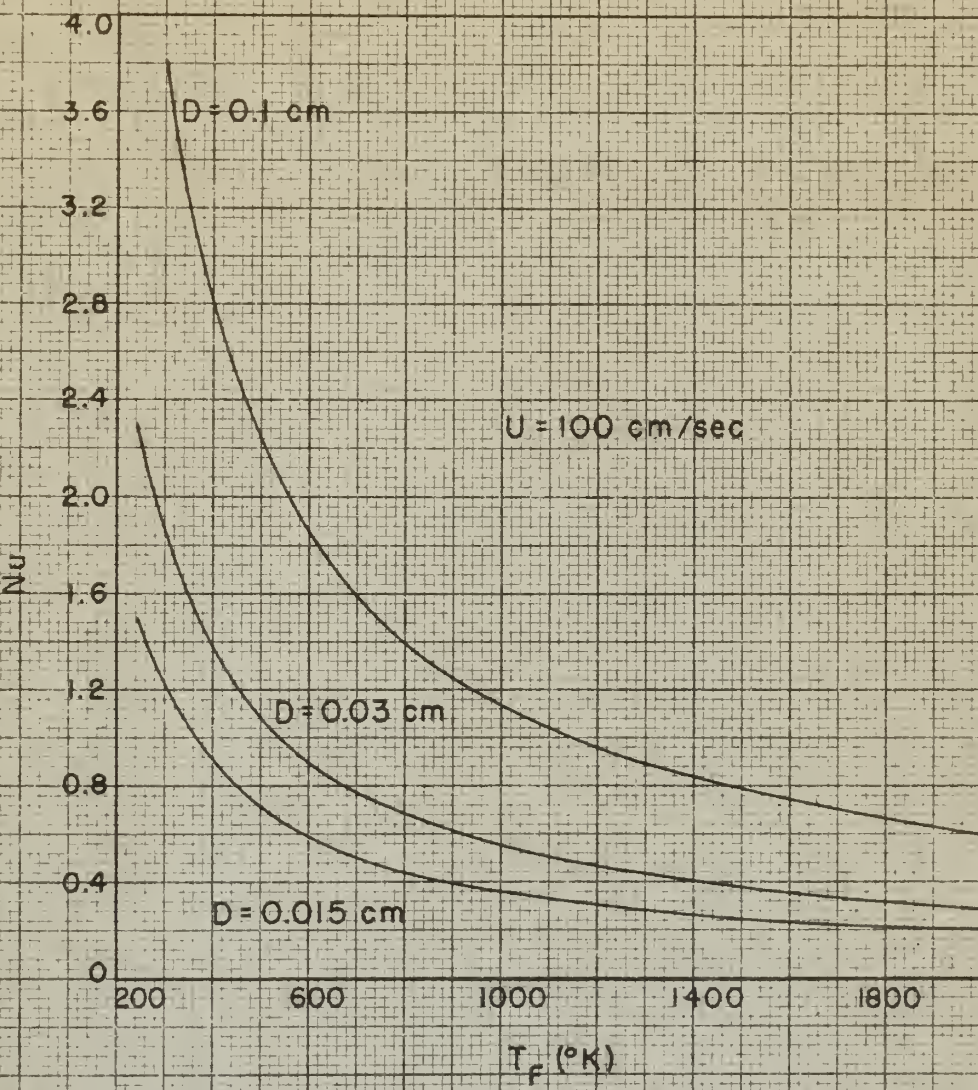


Figure 4. Nu vs FILM TEMPERATURE

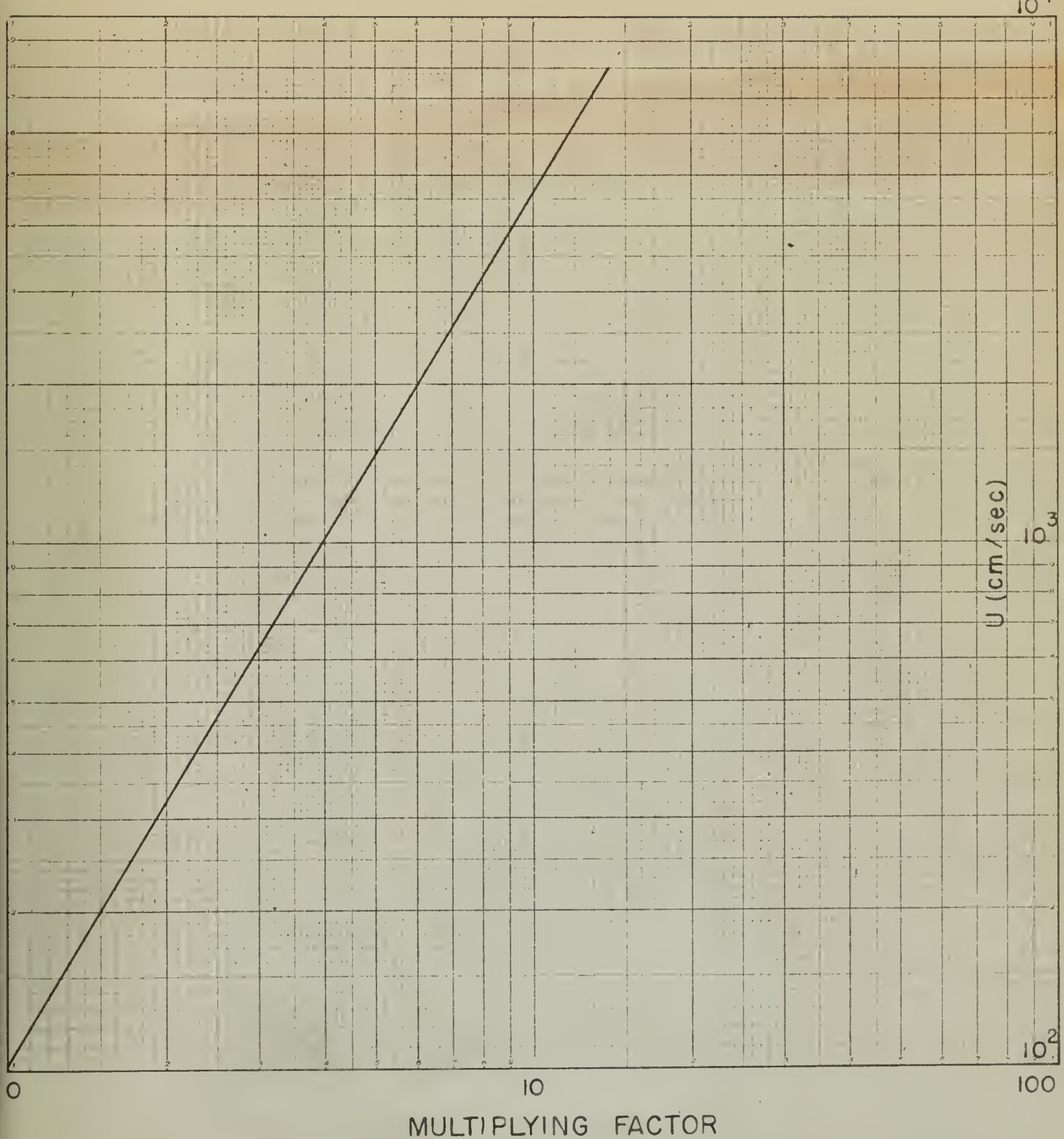
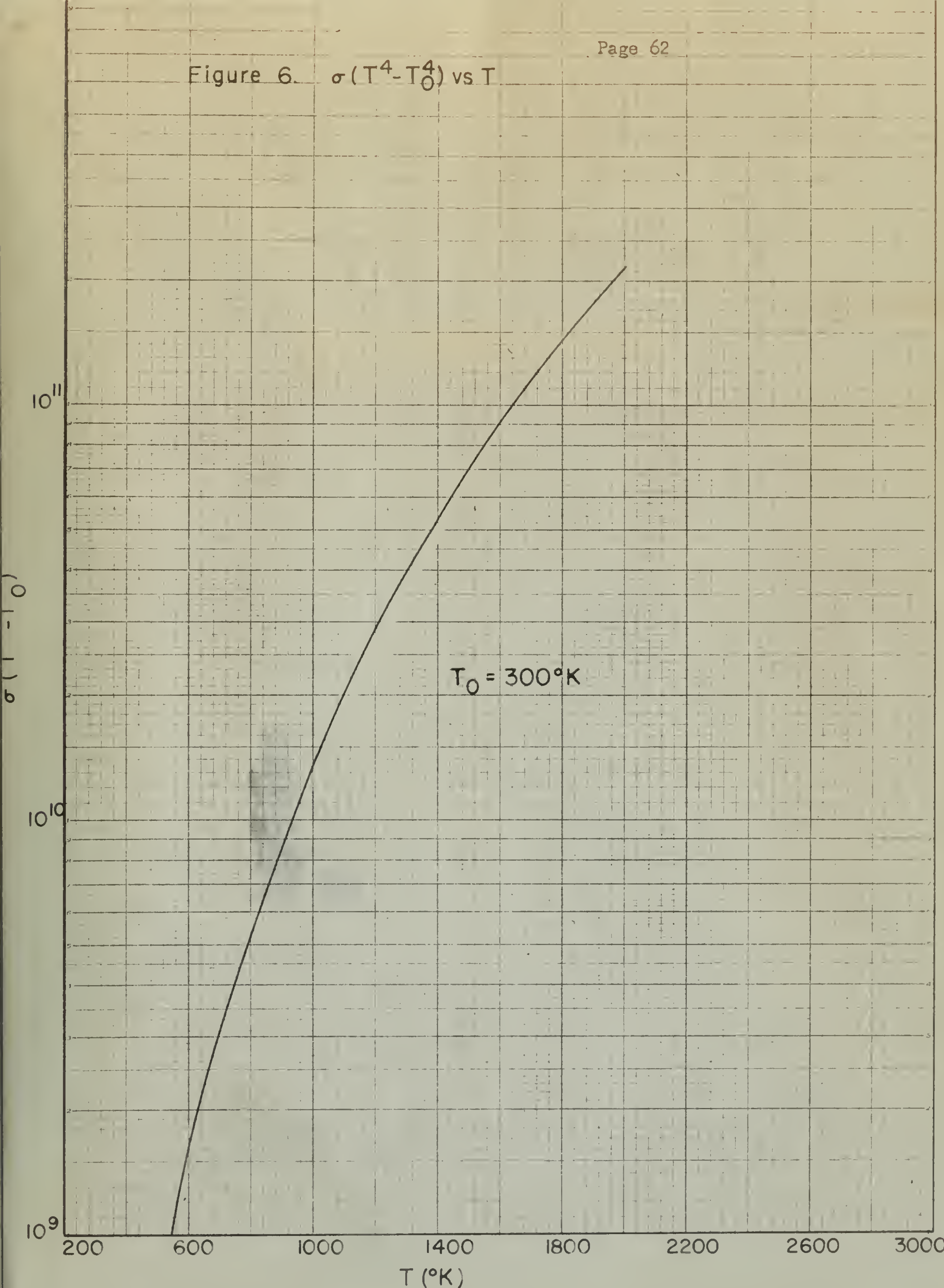


Figure 5. VELOCITY MULTIPLYING FACTOR to be APPLIED to Nu as PLOTTED in Figure 4

Figure 6. $\sigma(T^4 - T_0^4)$ vs T



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